

Chapter 3

Solar Energy

3.1 The Sun as Energy Source

3.1.1 General Notions

Designing a system for solar energy conversion into thermal energy or electricity is based on accurate assessment of the solar radiation in the given location and on the knowledge of solar radiation properties. The Sun is the closest star to the Earth, at the average distance of 1.5×10^{11} m.

Schematic structure of the Sun is shown in Fig. 3.1, and the geometric relations of the “Sun–Earth” system – in Fig. 3.2. The Sun’s energy is the result of several nuclear fusion reactions, the main being the process in which hydrogen (four protons) merges and forms helium. The mass of alpha particle (helium nucleus) is less than the mass of four protons, the difference in mass is converted into energy according to Einstein’s formula $E = mc^2$.

Sun’s diameter is about 110 times bigger than the Earth’s diameter: 1.39×10^9 m, and respectively, 1.27×10^7 m. The solar core, with a radius of about $0.23R$ (R – radius of the solar disk) and a volume up 15% of the total, is a thermonuclear fusion reactor. Its temperature is estimated at $(8\text{--}40) \times 10^6$ °K and 90% of energy is released. The core has a density 100 times bigger than water density and its mass is 40% of the total mass. At a distance of $0.7R$ from the Sun core, the temperature falls to $130,000^\circ\text{K}$ and the density drops to 70 kg/m^3 . The area between 0.7 and $1.0R$ is called the convection zone (it is considered that the thermal convection processes are the main ones). The temperature falls to $5,000^\circ\text{K}$ and density is very low – about 10^{-5} kg/m^3 .

The Earth revolves in orbit around the Sun, that is approximately circular (circumference deviation does not exceed 1.7%). The average distance between the Sun and the Earth (Fig. 3.2), called the astronomical unit is equal to $1,495 \times 10^{11}$ m. The Sun, as viewed from the Earth’s surface, represents a disk with an angular diameter $32'$. Solar radiation can be modelled with that of an absolutely black body

Fig. 3.1 Simplified structure of the Sun

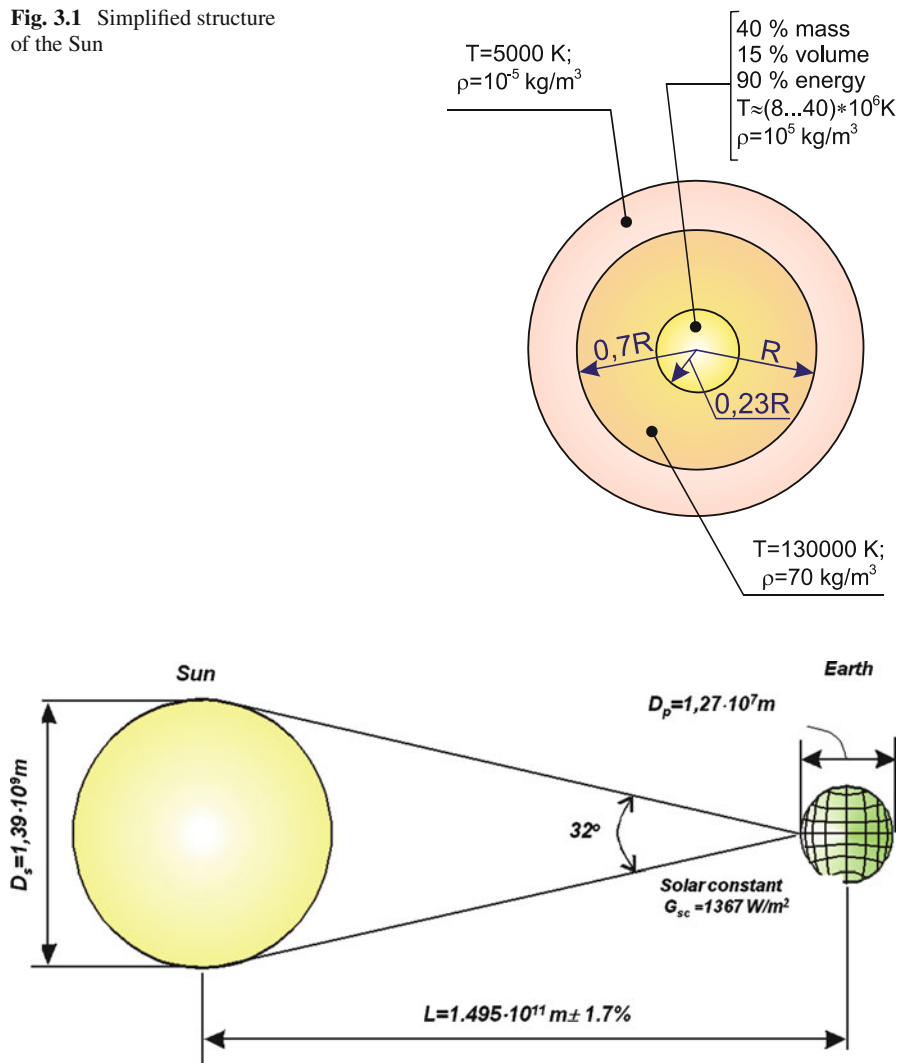


Fig. 3.2 Geometry of the “Sun-Earth” system

with actual (effective) temperature of about $5,777^\circ\text{K}$ (it is a model introduced in physics to characterize the radiation spectrum of a body with a constant temperature T [1]). Calculations of the absolutely black body radiation and measurement results show that 6.4% of energy is carried by ultraviolet band of electromagnetic waves ($\lambda = 0-0.38\text{ }\mu\text{m}$), 48.0% – by the visible band ($\lambda = 0.38-0.78\text{ }\mu\text{m}$) and 45.6% – by the infrared band ($\lambda > 0.78\text{ }\mu\text{m}$). It is important to know the energy spectrum of solar radiation in order to understand the effects of atmosphere on the radiation coming from the Sun and make a correct choice of materials for solar collectors or photovoltaic cells.

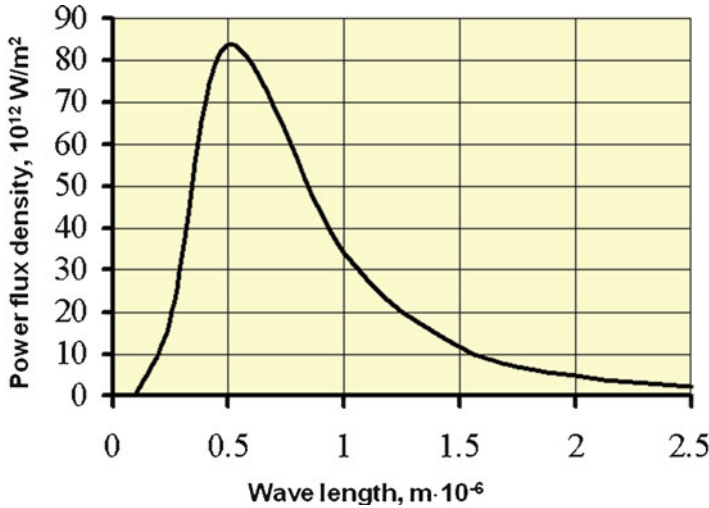


Fig. 3.3 Spectral radiation of the black body

In terms of energy, solar radiation is of interest, which, in fact, is a mix of electromagnetic waves ranging in the wavelength range (0.2–2.5) μm . Wave energy with a length more than 2.5 μm can be neglected. Some definitions, below, will be helpful to properly understand this chapter. *Irradiance* is measured in W/m^2 and is the momentary power flux density of solar radiation. For example, the irradiance equal to 1,000 W/m^2 means that an energy flux equal to 1,000 J falls every second on one square meter of surface. *Irradiation* is measured in MJ/m^2 or kWh/m^2 and is the *energy density* of solar radiation. It is obvious that irradiation is the irradiance integral within a defined period of time – 1 h, day or month. In most cases in the literature, the first term is replaced with *power density of solar radiation*, and the second – by *solar radiation: hourly, daily, monthly or yearly*.

In the calculation of photovoltaic systems the energy density of solar radiation, measured in kWh/m^2 , is often expressed as *peak Sun hours*, which means *the time* in hours with a power density 1 kW/m^2 required to produce a daytime solar radiation equivalent to that obtained after the integration of energy density during the day.

Analytical relationship between the power density, temperature and wave length is given by Planck's formula [2]:

$$W_\lambda = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}, \text{ W}/\text{m}^2, \quad (3.1)$$

where

$h = 6.63 \times 10^{-34} \text{ W s}^2$ is the Planck's constant;

$k = 1.38 \times 10^{-23}$ is the Boltzmann's constant;

$c = 299,722,458 \text{ m/s}$ is the speed of light in vacuum.

Analytical expression (3.1) allows modelling of solar radiation with high accuracy. Figure 3.3 shows the power spectral density on the surface of the Sun,

calculated in accordance with Eq. 3.1 for the effective temperature of the absolutely black body equal to 5,800°K. It is the radiation power density on the surface of the Sun. Running the distance of about 150 million km (see Fig. 3.2), total extraterrestrial power density (at the boundary between the Earth's atmosphere and the outer space) decreases to a value called the solar constant. The solar constant S is the energy received from the Sun per a unit of time for a surface perpendicular to the Sun, located at the average distance between the Sun and the Earth, outside the atmosphere. In fact, due to orbital eccentricity of the Earth, extraterrestrial radiation varies. Based on measurements taken in the late 90s of the twentieth century, the World Radiation Centre (WRC) has accepted the mean solar constant equal to 1,367 W/m², with the uncertainty of 1.0% [3].

Conventional air mass, m , characterizes the way of solar beam through the atmosphere to the sea level. For the extraterrestrial space or if the land would not have the atmosphere, $m = 0$. At the Equator, while the Sun is in its zenith, the solar beam runs the shortest distance, $m = 1$. For zenithal angles θ_Z (zenithal angle – the angle between the vertical circle and direction to the Sun), between 0° and 70°, the air mass m can be calculated by the expression

$$m = \frac{1}{\cos \theta_Z}. \quad (3.2)$$

If θ_Z is equal to 60°, the air mass $m = 2$, i.e. the solar ray will run a way through the atmosphere twice bigger than if $\theta_Z = 0^\circ$. Obviously, in the second case, the solar beam will be more mitigated and it will carry less energy. This explains the decrease of solar radiation intensity in the northern hemisphere, and in the southern hemisphere, respectively, compared to the equatorial zone.

Beam or direct radiation is the received radiation from the Sun without being scattered by the atmosphere (see Fig. 3.4). The shadow of an object appears only when direct radiation occurs. Further, direct radiation will be marked with B.

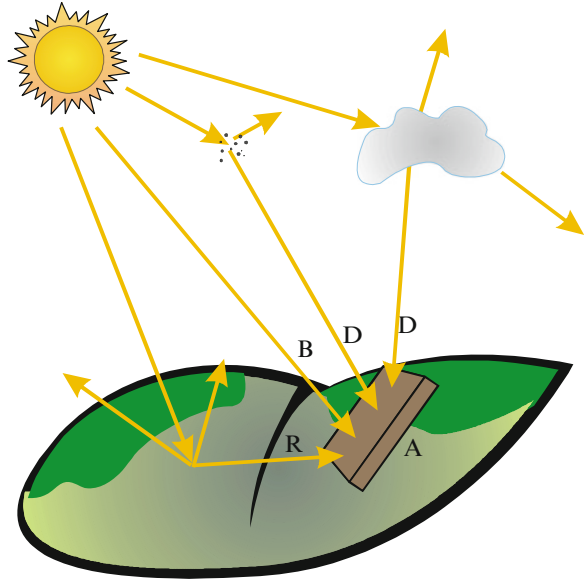
Diffuse radiation will be denoted by D. The solar ray passing through the atmosphere is scattered, i.e. diffused in all directions (see Fig. 3.4). Diffuse radiation is always present, even on a clear day this component is about 10%. In this case, solar rays are scattered by the molecules of oxygen, carbon dioxide, dust particles, etc., and the sky becomes blue. If the sky is overcast then direct radiation is zero, and the effect of diffuse radiation is present only. Because of the diffuse radiation, the light penetrates even through a window facing the north.

Global solar radiation: The sum of the two components makes the global radiation G on some surface. In most cases, it is measured and used as the notion of global radiation on a horizontal surface. From the definition follows:

$$G = B + D \quad (3.3)$$

Albedo or reflected radiation is denoted by R. Usually, one operates with the radiation reflected by the Earth's surface, which falls on the solar collector or photovoltaic panel. In most cases, this component is not taken into consideration,

Fig. 3.4 Components of solar radiation at absorbing surface A: B – direct; D – diffuse; R – reradiation



except for collectors or bifacial photovoltaic panels (both surfaces are operating – the one oriented to the Sun and another oriented to the Earth's surface). Thus, the total radiation incident on the surface of a body would be equal to the sum of direct radiation that is diffused and reflected (Fig. 3.4):

$$G = B + D + R \quad (3.4)$$

3.1.2 Solar Radiation on the Earth Surface

Above it was mentioned that the radiant power density S in the outer space is constant and equal to $1,367 \text{ W/m}^2$. Each period, the Earth gets the same amount of energy calculated by multiplying the surface S with the surface exposed to irradiation and with the period, we are interested in (a second, a minute, an hour etc.). The surface exposed to irradiation is equal to πR^2 , where R is the radius of the Earth, and the total area of the globe – with $4\pi R^2$. Thus, the average radiant power density S_{med} collected by the Earth will be:

$$S_{med} = \frac{S}{4} = \frac{1367}{4} = 342 \text{ W/m}^2 \quad (3.5)$$

Further the analysis of solar radiation properties on the Earth surface will be done, on the assumption that the average radiant power density at the boundary between the Earth's atmosphere and the outer space is constant. The solar rays

passing through the atmosphere are subject to significant changes. Some are absorbed by the molecules of air, others – scattered (diffuse component) and some enter the atmosphere without being affected (direct component) and are absorbed or reflected (reflected component) by objects on the Earth's surface (see Fig. 3.4). Two major effects influence very much the extraterrestrial radiation that runs the atmospheric layer:

- Diffusion of Sunlight by molecules of air, water and dust.
- Absorption of Sunlight by molecules of ozone O_3 , water H_2O and carbon dioxide CO_2 .

Diffusion of solar radiation is caused by the interaction of electromagnetic wave with wavelength λ and the molecules of air, water and dust. The intensity of interaction depends on the length of the pathway run by the beam through the atmosphere defined by the air mass m (see expression [3.2]), the number of particles and their size in comparison with the wavelength λ . According to Rayleigh's theory [4], the diffusion coefficient, which is due to the interaction of the Sun ray with the air molecules, is proportional to λ^{-4} and is significant for the wavelengths less than $0.6 \mu m$. Phenomena related to ray diffusion by molecules of water, dust, etc., are quite complicated, their detailed description being given in [5, 6]. The absorption of Sun rays by the atmosphere is due to ozone, oxygen, water and carbon dioxide molecules. Spectral radiant power distribution (Fig. 3.5) is presented for two cases: (1) $m = 0$, extraterrestrial radiation, i.e. the upper boundary of the atmosphere and (2) at the sea level for $m = 1.5$ (azimuthal angle $\theta_z = 48^\circ$, angle of Sun elevation above the horizon, $\alpha = 42^\circ$). There is a strong absorption band of ultraviolet radiation with a wavelength less $0.3 \mu m$ by the molecules of ozone (the ozone layer is the protection screen of the biosphere from the killing ultraviolet rays), a high transparency of the atmosphere in the visible band $0.4 < \lambda < 0.76 \mu m$, and a strong absorption of spectrum band infrared radiation. In other words, our atmosphere is transparent to visible band radiation and is opaque – in the infrared band. Because of these two effects, solar radiation on the Earth's surface decreases significantly and the irradiation or instantaneous power density peaks about $1,000 W/m^2$, which takes place at noon, under clear sky.

3.1.3 The Sun and the Global Energy Balance

The Sun is the main source of energy that defines the climate on the Earth. In accordance with expression (3.5), every square meter of the outer covering of the atmosphere receives $342 W$, of which 31% or $106 W$ is immediately reflected into the space by the clouds, the atmosphere and the land surface (see Fig. 3.5). The rest, i.e. $236 W/m^2$, is absorbed by the land, ocean surface water and, partially, by the atmosphere, warming them. The Earth's surface delivers into space the same quantity of energy ($236 W/m^2$), but already in the infrared wavelength band: partly, the atmospheric cover, the clouds and water vapours, which, condensing, become

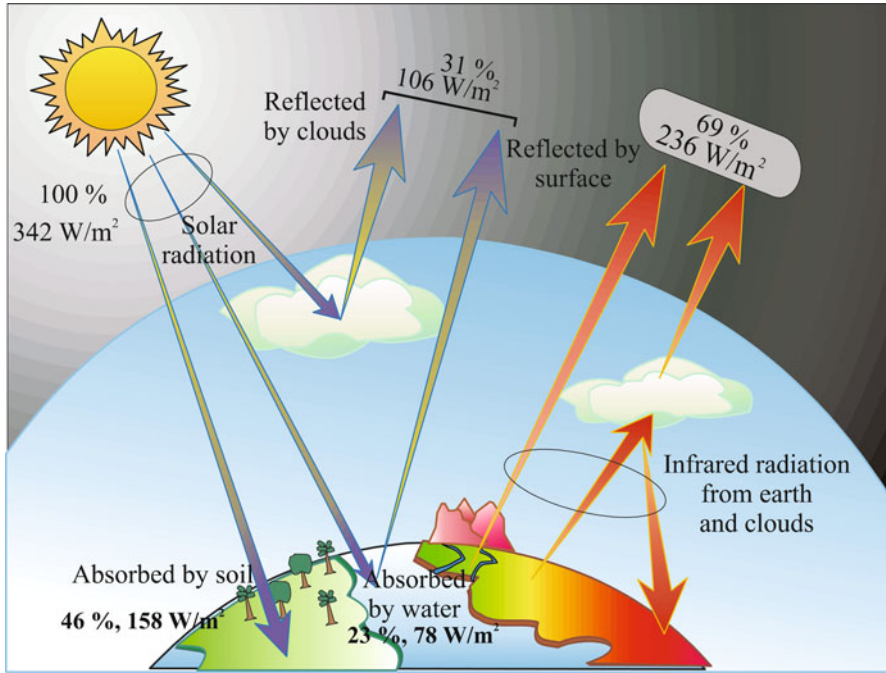


Fig. 3.5 Simplified balance of energy fluxes in the “Earth surface-atmosphere” system

cooler and transmit heat to the atmosphere (see Fig. 3.5). Due to the exchange of energy between the Earth’s surface, the atmosphere and the outer space, a constant average global temperature of about 15°C maintains at the sea level, which decreases rapidly with height increasing, reaching -58°C in the upper troposphere. A natural question arises: to which physical phenomena this balance is due to and can it be damaged? The answer is found addressing again the theory of absolute black body, which is modelling either the Sun with actual temperature of $5,777^{\circ}\text{C}$ or the Earth with effective temperature equal to T_e .

3.1.4 Greenhouse Effect Simulation

The Earth’s atmosphere contains several gases called greenhouse gases (GHG): carbon dioxide CO_2 , methane CH_4 , nitrogen oxide N_2O , and water vapours H_2O . A common property of GHG lies in their absorption by its molecules in the infrared band radiation emitted by the Earth’s surface, atmosphere and clouds. The certain molecule begins to vibrate and, in its turn, emits the same spectrum of infrared radiation which is absorbed by other greenhouse gas molecules. Thus, the phenomenon of absorption – emission – absorption leads to energy conservation in the lower layer of the atmosphere. In other words GHG has the same role as

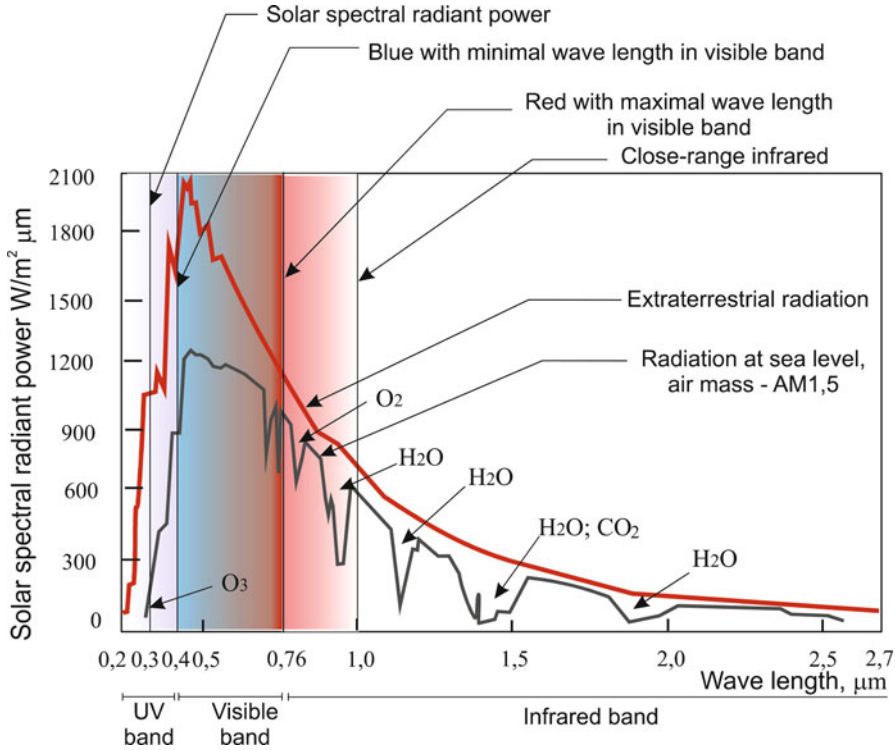


Fig. 3.6 Spectral distribution of power flux (radiant) density

the glass roof of a greenhouse. The term “greenhouse effect” was introduced by meteorologists from the early nineteenth century [7], at that time had no negative implication and was used to describe the natural greenhouse effect due to which the average temperature on the Earth remains constant and is about 15°C. The greenhouse effect has a crucial role in maintaining life on Earth. If the greenhouse effect would not occur then the temperature on the Earth’s surface would be determined by the balance between the quantity of energy released by the Earth to space and the received one from solar radiation. In accordance with the Stefan-Boltzmann’s law [1] the amount of energy emitted by a body with effective temperature T_e is determined by the relationship

$$We = \sigma \cdot A \cdot T_e^4, \quad (3.6)$$

where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ is Stefan-Boltzmann’s constant; A – body area.

Equation 3.6 is obtained as a result of the integration of expression (3.1) of the spectral power density. In the case of Earth $We = 4\pi R^2 \sigma T_e^4$. In addition, the Earth receives from the Sun a quantity of energy equal to 0.69 S/4 (see Eq. 3.5 and Fig. 3.6). In condition of thermal balance, the quantity of the received energy

equals the amount of energy emitted from where we get the actual temperature of the Earth's surface T_e :

$$T_e = \sqrt[4]{\frac{0.69S}{4\sigma}}. \quad (3.7)$$

For $S = 1,367 \text{ W/m}^2$, from Eq. 3.7 we obtain the effective temperature of the Earth's surface $T_e = 254^\circ\text{K}$ or -19°C . It is clear that life on Earth in such conditions as it exists would not be possible.

Since the second half of the twentieth century and, especially, nowadays, it is often spoken of the so-called *greenhouse effect*, but already with a negative sense, linked primarily to the phenomenon of *global climate change*. From the point of view of environmental professionals that is due to the anthropogenic impact on the natural balance.

Heat balance of the Earth can be damaged by either natural or human activity. Volcanic eruption causes a sudden increase in dust in the upper layers of the atmosphere, burning fossil fuels leads to increased GHG emissions, massive cutting of forests, urbanization, introduction of new agricultural land lead to changing the refraction coefficient (albedo). Because of these effects, the variations of energy flows received and transferred by the Earth's surface occur. These variations can be negative or positive. In both cases, the climate system will respond to establish a new thermal balance. Positive changes will tend to establish a higher temperature of the Earth's surface and negative changes will tend to opposite effects. Recent studies show a predominance of positive change and global warming occurs.

3.2 Solar Energy Potential

3.2.1 Global Solar Energy Potential

The greatest theoretical potential of renewable energy is solar energy (about 89,000 TW, see Fig. 1.40). Among the components of solar energy, direct normal solar radiation is most important in terms of energy conversion.

Direct normal radiation is affected by both climatic conditions and the distance from the Sun through the atmosphere. Figure 3.7 shows a typical chart of diurnal and seasonal distribution of direct normal radiation (DNR) in the Mojave Desert, California, USA [8].

Global solar theoretical energy potential is very big, but various factors, such as areas with limited Sunlight, weather conditions and performance of conversion systems dramatically reduce the energy potential explored. Still the explorable energy potential remains very high, being comparable to global energy production (Table 3.1). The most favourable areas, in terms of solar energy conversion, are those at the equator, and in particular, in the desert, where such a negative effect (for solar energy conversion) as rains rarely occurs. Also, some solar energy

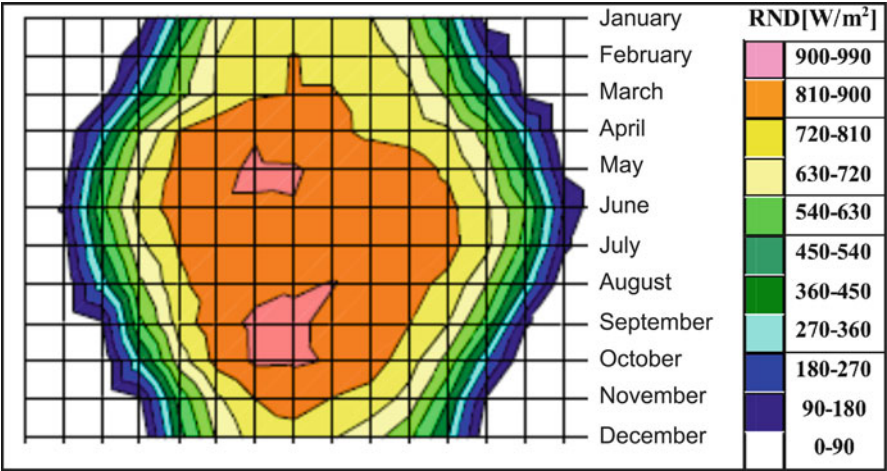


Fig. 3.7 Distribution of daily and seasonal normal direct radiation in Mojave desert, California, USA

Table 3.1 Potential of solar electrical energy generation by thermodynamic conversion

Characteristics	Energy quantity (TWh/an)
Overall solar radiation at the Planet’s surface	240×10^6
Desert surfaces occupy 7% of the total Planet’s surface	17.0×10^6
Available direct fraction of the radiation (approx. 70%)	11.2×10^6
Annual average efficiency of solar energy conversion into electrical energy (about 15%)	11.2×10^6
Part of semi-arid and arid locations for solar collectors units in living areas and with access to infrastructure (1% of the desert surface)	16.8×10^3
Overall production of electrical energy in 2000	15×10^3

conversion systems require large areas, which, in cases of developed agricultural areas are cut out of the agricultural circuit. From this point of view, the biggest solar energy conversion systems are located in the deserts of the USA, Australia, arid areas of Spain, etc.

3.2.2 Estimation of Available Solar Radiation

3.2.2.1 General View

To design a facility for solar energy conversion into heat or electricity it is necessary to know the available solar radiation on the collecting surface either of the solar collector or of the PV module (panel). However, solar radiation is a variable function, which depends on several factors: *latitude and altitude of the location*,

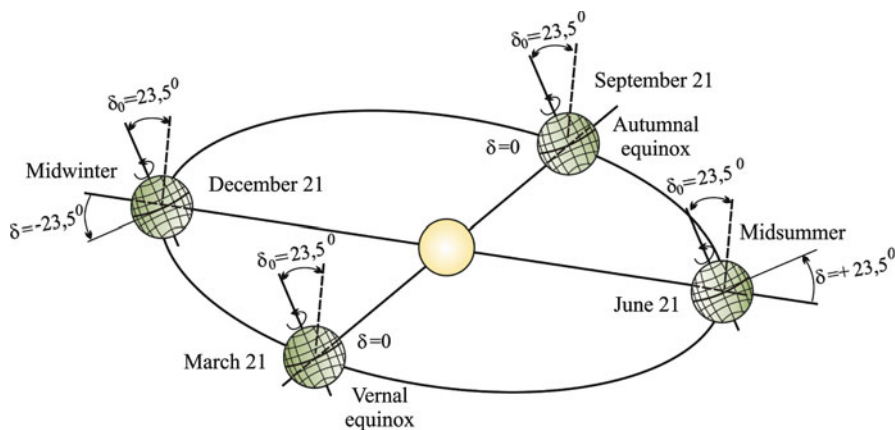


Fig. 3.8 Earth's orbit and the declination angle δ

season, day, hour, degree of cloudiness, dust content, water vapours and aerosols in the atmosphere. It is obvious that there cannot be one or more mathematical expressions, which would allow calculation of solar radiation, taking into account all these factors, in particular, those with random nature – the cloudiness, content of dust, aerosols, etc.

Designing a solar plant and forecasting its future productivity is based on systematic measurements of solar radiation components carried out in the past and available in the publications of Hydrometeo State Department (see Annex A1). In most cases, the measurement results are used for a horizontal surface of the direct and diffuse radiation for a period of an hour, a day or a month. Calculations based on the duration of an hour are more accurate, but require a heavy workload. The methodology is described in detail in [4]. In this manual, daily and monthly data on solar radiation and the isotropic model of the celestial vault will be used. To understand the essence of the calculations, at first, some notions of astronomy, in particular, the analytical relations that describe the apparent motion of the Sun around the sky will be addressed.

The Earth rotates in an elliptical orbit around the Sun during 1 year with the Sun in one of the focal points. Also, the Earth rotates around its axis, making one revolution in 24 h. The Earth's axis of rotation has a fixed direction in space and is inclined at angle $\delta_0 = 23.5^\circ$ towards the normal line in the orbit plane (Fig. 3.8).

The angle between the Sun direction and the equatorial plane is called the declination angle δ and varies throughout the year from $+23.5^\circ$ when the summer solstice (June 21) to -23.5° at the winter solstice (December 21). On March 21st, and respectively, September 21 the declination $\delta = 0$ and the day time and the night time are equal. According to [4] the declination can be calculated using the formula:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right), \quad (3.8)$$

Table 3.2 Number of the average day for every month and its values n [4]

Month	n for i day of the month	For the average day of the month		
		Date	n , number of days per year	δ (degree)
I	i	17	17	-20.9
II	$31 + i$	16	47	-13.0
III	$59 + i$	16	75	-2.4
IV	$90 + i$	15	105	9.4
V	$120 + i$	15	135	18.8
VI	$151 + i$	11	162	23.4
VII	$181 + i$	17	198	21.2
VIII	$212 + i$	16	228	13.5
IX	$243 + i$	15	258	2.2
X	$273 + i$	15	288	-9.6
XI	$304 + i$	14	318	-18.9
XII	$334 + i$	10	344	-23.0

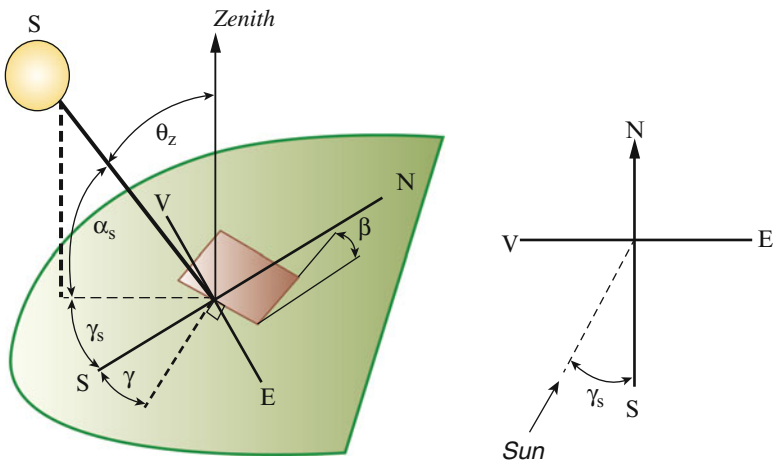


Fig. 3.9 Explications of angles: angle of dip β , azimuthal angle γ ; solar azimuth angle γ_s ; solar climbing angle α_s ; zenithal angle θ_z

where n is the number of days of the year, considering as the first day – January 1st.

If calculations are made based on monthly average variables, it is recommended to use the average number of days for each month and the number n of the day presented in Table 3.2. Geometric relationship between an arbitrarily oriented plane to the Earth and the direct Sunlight that falls on this plane at any moment, the Sun’s position against this plane can be described in terms of several angles. The definition of one angle – the angle of declination – has been given above. Definitions of other angles and other necessary analytical expressions are presented below. Geometric interpretations correspond to Figs. 3.9 and 3.10.

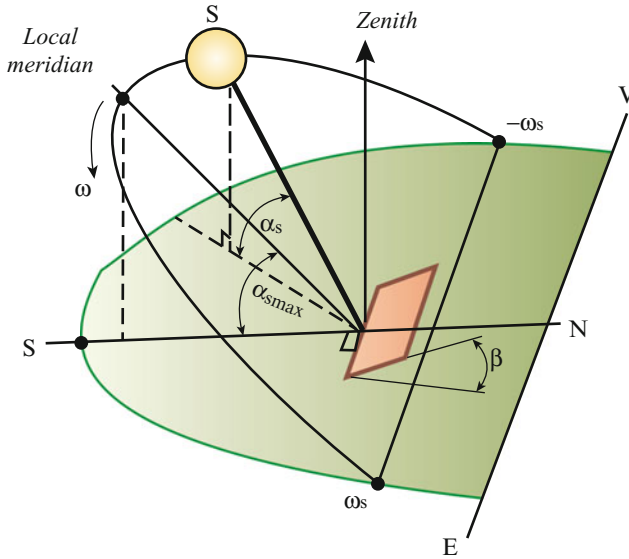


Fig. 3.10 Hour angle ω , sunrise angle ω_s and sunset angle $-\omega_s$

Latitude Φ is the angle measured from the equator to the point of interest on the Earth's surface. It is considered positive for the northern hemisphere and negative – for the southern hemisphere.

Angle of dip β of the plane is the angle between the plane surface in question and the horizontal surface, $0 \leq \beta \leq 180$ (Fig. 3.9). For normal solar units the maximum value does not exceed 90° .

Azimuthal angle γ is the angle between the horizontal plane projection of the normal line on the plane and the local meridian (Fig. 3.9); it is equal to zero for the plane that faces the south, negative – to the east, positive – to the west; $-180 \leq \gamma \leq 180$.

Solar azimuthal angle γ_s is the angle between the southern direction and the projection on the horizontal plane of the direct radiation of the solar beam (Fig. 3.9 to the right); the angles measured from the southern to eastern direction are negative, the measured angles to the west are positive.

Solar climbing angle α_s is the angle between the horizon and the line joining the Sun and the point of interest, i.e. the solar beam incident at the point of interest (Fig. 3.9).

Zenithal angle θ_z is the angle between the vertical and the line joining the Sun and the point of interest, i.e., the angle complementary to angle α_s (Fig. 3.9).

Hour angle ω determines the position of the Sun in the sky at the given moment. It is equal to zero when the Sun crosses the local meridian, in other words, at noon, positive – to the east and negative – to the west (Fig. 3.10). Accordingly, $+\omega_s$

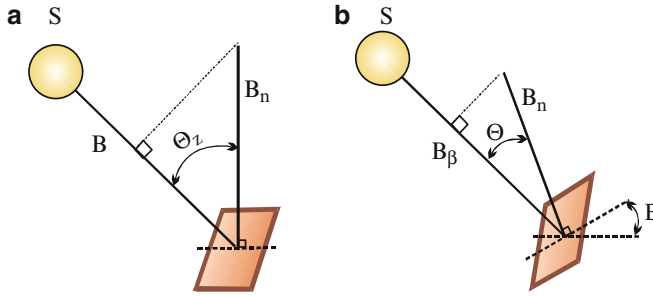


Fig. 3.12 Direct solar radiation on an horizontal (a) and inclined (b) planes

when the Sunrise angle, α_s , (Fig. 3.10) will be maximum, and the road map of the solar ray will be minimum and the hour angle $\omega = 0$. This situation will occur when direct radiation falls perpendicularly on the surface of collector C. From Fig. 3.11 it results that $\beta = 2.13$, and from the expression (3.10):

$$\cos\theta_z = \cos\Phi\cos\delta + \sin\Phi\sin\delta = \cos(\Phi - \delta), \quad (3.12)$$

From which we obtain:

$$\beta = \Phi - \delta. \quad (3.13)$$

Table 3.2 lists that, for the period researched, the average value of declination is equal to 15° and for the central area of the Republic of Moldova we get $\beta = 47 - 15 = 32^\circ$. For the cold season of the year declination is equal to 15° and the angle of inclination should be $\beta = 47 + 15 = 62^\circ$. It is obvious that the period can be taken arbitrary – an hour, a day, a month or a certain season. Thus, the issue of estimating solar radiation on an inclined plane in the general form, occurs. The solution is given in the next paragraph.

3.2.2.2 Solar Radiation on an Inclined Plane

In most cases, we rely on information about the solar radiation on a horizontal plane. At the same time, it is necessary to know the direct and diffuse components of radiation in terms of a solar collector or photovoltaic panel. Equation 3.13 determines the angle of inclination of the collector or panel for a period of 6 months – the warm or cold periods. The best solution would be to follow the apparent motion of the Sun in the sky, so that direct radiation falls perpendicular to the surface of interest. But the tracking mechanism is complicated and expensive, and usually used in facilities with solar radiation concentration.

Flat solar systems are built with no tracking, are oriented to the south and are mounted at an angle to the horizon optimal for the given location and for the exploitation duration during the year. Figure 3.12 presents the direct solar radiation

B on the horizontal plane (a) and B_β on an inclined plane towards horizon with the angle β (b). Perpendicular radiation on the plane surface is denoted by B_n . It is necessary to determine the ratio between the B_β and B . The ratio of direct radiation on an inclined plane and on the horizontal plane by R_b should be noted. Thus, $R_b = B_\beta/B$. From Fig. 3.12 we have:

$$B = B_n \cos \theta_z; B_\beta = B_n \cos \theta. \quad (3.14)$$

the ratio R_b :

$$R_b = \frac{B_n \cos \theta}{B_n \cos \theta_z} = \frac{\cos \theta}{\cos \theta_z}, \quad (3.15)$$

where θ is the solar altitude angle – the angle between the normal line of the plane to the direction of the solar beam. For the horizontal plane (Fig. 3.14) $\theta_z = \theta$.

For an arbitrarily set plane the functions $\cos \theta$ and $\cos \theta_z$ are expressed by combinations of functions of the angles discussed above – δ , Φ , β , γ and ω [4]:

$$\begin{aligned} \cos \theta = & \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \varpi + \\ & + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \varpi + \cos \delta \sin \beta \sin \gamma \sin \varpi. \end{aligned} \quad (3.16)$$

From which for $\beta = 0$, we obtain $\cos \theta_z$:

$$\cos \theta_z = \cos \phi \cos \delta \cos \varpi + \sin \phi \sin \delta. \quad (3.17)$$

In most cases, the solar collector or the photovoltaic panel are installed to south with the active side, and $\gamma = 0$ for the northern hemisphere and $\gamma = 180^\circ$ – for the southern hemisphere. Substituting in Eq. 3.15 we get:

$$R_b = \frac{\cos(\phi - \beta) \cos \delta \cos \varpi + \sin(\phi - \beta) \sin \delta}{\cos \phi \cos \delta \cos \varpi + \sin \phi \sin \delta}. \quad (3.18)$$

Equation 3.18 is used to determine the optimal angle β for periods of 1 h or 1 day. When operating with monthly values of solar radiation, Eq. 3.18 is modified:

$$\bar{R}_b = \frac{\cos(\phi - \beta) \cos \delta \cos \varpi'_s + (\pi/180) \varpi'_s \sin(\phi - \beta) \sin \delta}{\cos \phi \cos \delta \cos \varpi_s + (\pi/180) \varpi_s \sin \phi \sin \delta}, \quad (3.19)$$

where ϖ'_s is the hour angle of the Sunset towards the inclined plane; ϖ_s – is the hour angle of the Sunset towards the horizontal plane.

Angles ϖ'_s and ϖ_s are determined from the relations:

$$\omega_s = \arccos(-tg\phi \cdot tg\delta), \quad (3.20)$$

$$\omega'_s = \min\{\omega_s; \arccos[-tg(\phi - \beta) \cdot tg\delta]\} \quad (3.21)$$

Table 3.3 Typical values of the albedo (reflection coefficient), ρ

Land characteristics	ρ
Ploughing	0.2
Land covered with verdure	0.3
Sandy desert	0.4
Snow	0.7

The calculated values of ratio R_b are presented in [4], in graphical and tabular form, depending on the difference of angles $\phi - \beta$ (over each 5°) and the latitude of the location ϕ (over each 5°). For the ratio value R_b calculated, the direct component of solar radiation on an inclined plane is determined:

$$B_\beta = R_b \cdot B. \quad (3.22)$$

Other components of solar radiation, diffuse and reflected, are determined from the isotropic model of the celestial vault proposed by Liu and Jordan in 1961 and modified by Klein in 1977 [4]. Diffuse radiation on an inclined plane D_β is calculated by formula:

$$D_\beta = \frac{1}{2} (1 + \cos\beta) D, \quad (3.23)$$

where D is diffuse radiation on a horizontal plane (Annex A1).

Reflected radiation on an inclined plane R_β is calculated by formula:

$$R_\beta = \frac{1}{2} (1 - \cos\beta) \rho G, \quad (3.24)$$

where

ρ is the reflection coefficient of the Earth's surface (see Table 3.3);

G – is global radiation on a horizontal surface

In consequence, global radiation on an inclined plane is equal to the sum of the three components—direct, diffuse and reflected radiation on the same plane:

$$G_\beta = R_b B + \frac{1}{2} (1 + \cos\beta) D + \frac{1}{2} (1 - \cos\beta) \rho G. \quad (3.25)$$

3.3 Solar Energy Conversion Systems

3.3.1 General View

Technologies for wider use of renewable energies must be simple and reliable, affordable in developing countries with low technological development, which have explorable and technical solar potential, but resources of materials are limited. They

must produce more energy during their life, should not deplete natural resources, and should not create products that have a negative impact on the society or the environment.

Solar energy can be converted in two ways:

- By thermal conversion (solar energy is converted into heat energy, used for heating, domestic water or electricity production);
- By using the photovoltaic effect (directly convert solar energy into electricity).

There is a wide variety of technical means to convert solar thermal energy, which can be divided into two groups:

1. Systems for direct and diffuse solar energy conversion into thermal energy at low temperatures. These do not require tracking the Sun and have a simple construction. This group includes:
 - Plane solar collector for water and air heating;
 - System of solar plane collector – flow turbine (solar towers);
 - System of accumulated heat solar energy plane collector – flow turbine (solar towers).

The last two systems are used to generate electrical energy.

2. Systems for Sun beam concentration, which convert the direct component of solar radiation into thermal energy under average and high temperatures (from several hundred to several thousand degrees). This group includes:
 - Cylindrical-parabolic trough systems;
 - Parabolic systems with different types of engines (steam turbine, Stirling engine, etc.);
 - Heliostat systems.

In most cases concentration systems are used to produce electricity. Cylinder-parabolic systems track the Sun as a single coordinate. A distinctive feature of solar electric systems (SES) consists in multiple energy conversion: solar radiation is converted into heat, then, using Carnot thermodynamic cycle or others, the heat is converted into mechanical energy. Finally, the electromechanical conversion is used to obtain electricity. From this point of view, photovoltaic conversion is superior compared to SES – solar radiation is converted directly into solar energy.

In all primary systems, solar radiation can be absorbed by a flat collector or can be concentrated optically using mirrors and lenses. Optimal choice depends on the technological-energy needs, location and weather conditions. Weather effects and solar angle have a major impact on the efficiency of concentrating collectors, which use only direct rays of the Sun. The combined effect of the Sunrise angles (zenith angle) has a major impact on SES efficiency (Fig. 3.13) [8].

Currently SES with Solar Energy Concentration is the most efficient and effective in terms of cost to generate electricity from solar energy (Table 3.4). However, hundreds of megawatts of SES generating capacities will be put into operation in the next few years and will make an important contribution to meeting the energy needs.

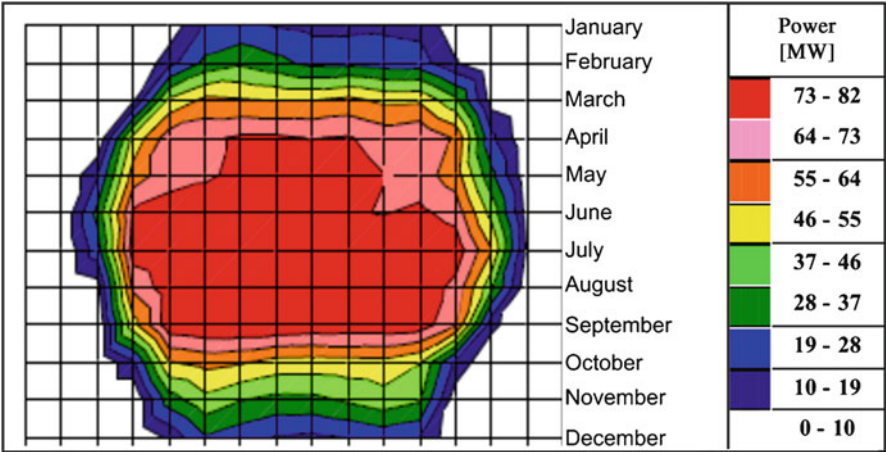


Fig. 3.13 Typical average production of solar electrical energy by SES

Table 3.4 Cost of solar electrical energy		
Technology	Capital investments cost (\$/kW)	Electrical energy cost (cent/kWh)
PV photovoltaic systems (crystalline silicon)	7,500–8,500	51.0
Technologies for SECS		
Stirling paraboloidal	2,650	16.7
Cylindrical-parabolic systems	2,877	13.4
Solar towers	2,713	9.0

What would be further development of these systems particularly advantageous in economic, environmental and social aspects?

Figure 3.14 shows two possible scenarios for the development of SES till 2020. Under both scenarios, SES cumulative installed capacity will increase substantially: in 2020 rates could reach 2,100 MW (under scenario 1), and respectively, 4,000 MW (under scenario 2).

3.3.2 Solar Systems for Water Heating

3.3.2.1 Brief History

Thermal conversion is the oldest and most widespread form of solar energy utilization. The first attempts to use solar energy for heating were made in Greece in the fifth century before Christ. At that time, the Greeks had already succeeded to exhaust their forestry resources and firewood was imported from Macedonia,

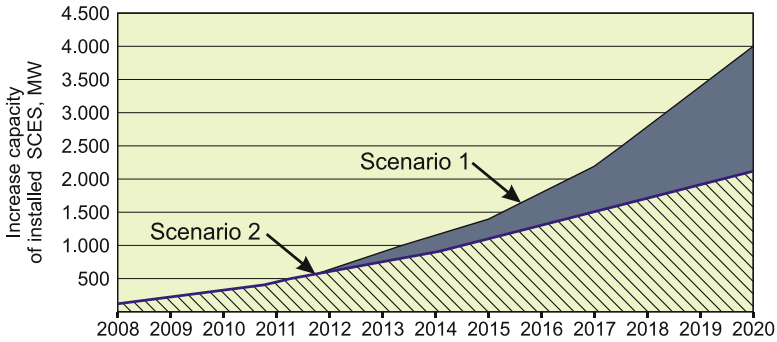


Fig. 3.14 Developing scenarios for SECS till 2020

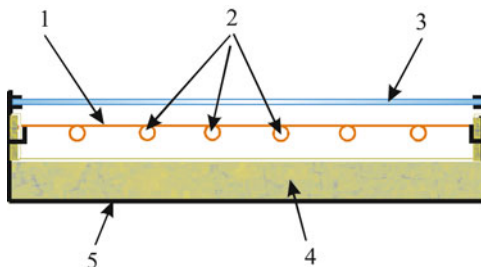
Cyprus and the Middle East. With the discovery of glass by the Romans, the development of bioclimatic concepts in buildings' construction started, which purpose was the efficient use of natural lighting, aeration (ventilation) of spaces in hot regions or heating the spaces in areas with moderate climates, using solar energy. The discovery of the greenhouse effect at the end of the eighteenth century, followed by the experiments undertaken by Horace de Saussure's (Switzerland, 1767), Augustine and Abel Mouchot Pifre (France, 1870), contributed to the first successful commercial systems for hot water production by using solar power (California, early twentieth century), then in Florida (between 1920 and 1950), water pumping, Frank Shuman (Egypt, 1912) [9–11].

Any black surface exposed to beams, called absorbing surface, transforms solar energy into heat. This absorbing surface is the simplest example of direct converter of solar radiation into thermal energy, called "*flat solar collector*". Solar thermal energy conversion includes several technologies: water heating with flat or vacuum collectors, drying agricultural products and medicinal plants, and in semi-finished wood processing, solar refrigeration, distillation of water, electricity generation, using thermodynamic process, etc. In this paragraph, the emphasis is on three technologies: hot water production, drying of agricultural products and residential space heating.

Technological aspects: Over the centuries, engineers and architects have improved the design of buildings for the most rational use of natural light and heat source – the Sun. From this point of view, the walls of buildings are heat accumulators, and the windows and rooms – are heat collectors, which allow penetration of visible band (short wave) solar radiation in the inside and do not allow infrared radiation (long wave) to leave the building. This technology, and, respectively, the systems used to achieve it were later called passive technologies, systems or methods to use solar energy. Passive systems are distinguished by the following two distinct features:

1. The processes for collecting, storing and using energy are integrated into the building structure. In other words, Sun beams heat the consumer directly;

Fig. 3.15 Constructive schema of the solar collector



2. Passive systems do not require mechanical energy to transport heat to the consumer or storage tank. Motion of air flows takes place under temperature differences between different layers.

On the contrary, active technologies or systems for solar energy conversion are equipped with special solar collectors in which solar radiation is converted into heat, and then through a heat carrier (usually water or air) is transported to the consumer or stored in the tank. The most common types of solar collectors are flat solar collectors not concentrating the radiation used to obtain maximum temperatures 150°C .

3.3.2.2 Flat Solar Collector for Water or Air Heating at Small Temperatures

Solar collector is a special heat exchanger that transforms the energy of solar radiation into solar energy. Also, the solar collector differs from most conventional heat exchangers (e.g., liquid-liquid heat exchangers), in which the heat transfer by radiation plays an insignificant role. In the solar collector, on the contrary, energy transfer to the liquid or gas is carried away through solar radiation with the wavelength ranging between 0.3 and $3\ \mu\text{m}$, and maximal power density of $1,000\text{--}1,100\ \text{W}/\text{m}^2$.

Flat-shaped solar collector can be designed to supply hot water at low temperatures of about $40\text{--}150^{\circ}\text{C}$. It uses both components of solar radiation – direct and diffuse, it does not require tracking the Sun in the sky, it generates low operating costs and has a much simpler construction compared to collectors with solar radiation concentration. This type of collector is the most widespread, as it is part of any water heating system, of residential areas, of solar drying chambers and refrigeration systems. It is technically and technologically highly advanced, and has a developed market and economic prospects. Figure 3.15 shows the design scheme of a solar collector for water heating. Its main components are: the so-called “black box” (5) with thermal insulation (4) of three walls, coated on the front by transparent surface (TS) (3).

Heat exchanger is metal plate-pipe type, absorbent surface (AS) (1) and pipes (2), respectively. In the case of the air collector, the heat exchanger is metal plate-air

channel. The solar collector operates based on two physical phenomena: absorption of solar radiation by a black body (Fig. 3.15, absorbing surface AS) and the greenhouse effect performed by the transparent surface TS. Artificial greenhouse effect is made in the case of the solar collector. TS surface is transparent to Sunbeams and opaque to infrared radiation that is heat, emitted by the absorbing surface AS. AS temperature increases and heat is transmitted to water running through pipes 2. Plate-pipe type heat exchanger is the main element of the collector shown in Fig. 3.15. Over the years, various technical solutions have been proposed for plate (1) – pipes (2) combination. The most viable solutions are shown in Fig. 3.16: coil (a), parallel tubes (b), channels consisting of two metal plates by contact method welding (c) or channels formed inside a plastic plate (d).

For the first two schemes the pipe-plate constructive contact is of particular importance. This must be done at the lowest thermal resistance. Next, the three usual technical solutions are presented:

- (a) Contact is performed by traditional welding of plate (1) and of pipe (2). The use of 1.5–2.0 mm thick steel plates is recommended. Often, welding is the main cause of obsolescence. Length of service does not exceed 5 years.
- (b) Contact is performed through plate deformation, so as to fold the pipe. It is a simple, highly productive at manufacturing and reliable solution. Over time, due to various linear thermal expansion of plate and pipe, a gap appears between them, increasing the thermal resistance of the plate-pipe contact, and, respectively, decreasing the heat transfer efficiency.
- (c) A copper plate (1) with a thickness not exceeding 0.2 mm is cold welded to the copper pipe 2 with inner diameter of 6 mm and outer diameter of 8 mm. Ultrasonic welding is used at wave frequency of 20 kHz and tool amplitude of 150 μm . The solution provides an 11 m/min productivity, a good quality welding (5) and a 20 years service life of the heat exchanger. Modern solar heat exchangers are manufactured using this technology.

In order to reduce heat loss through the space between the AS and TS, the heat exchanger of plate-pipe type is mounted in a glass cylinder (tube) out of which the air is removed. Thus, a significantly lower heat transfer by convection between the AS and TS areas occur and the collector efficiency increases.

The first vacuum tube collector has been proposed by Speyer in 1965. Figure 3.17 shows two design schemes of vacuum collectors. Tightly connected AS 2 and pipe 3 are placed into the glass tube 1. There is an essential difference between these two schemes. In the (a) scheme cold water enters through nozzle 5, is being heated and through nozzle 4 it is transported to the storage tank.

Both nozzles must be tightly connected to the glass tube. Tube (1) and pipe (3) expand differently, thus causing the loss of tightness between nozzle-glass tube connection. In the second scheme there is only one tight connection – the end (6) of tube (3). Heat transfer is done in the heat exchanger (8), to which end pipe (6), serving as condenser, and the pipe (7), through which water circulates, are mounted. Pipe (3) is partially filled with a liquid with a relatively low evaporation temperature. Under the action of heat absorbed by plate (2), the liquid evaporates, pressure

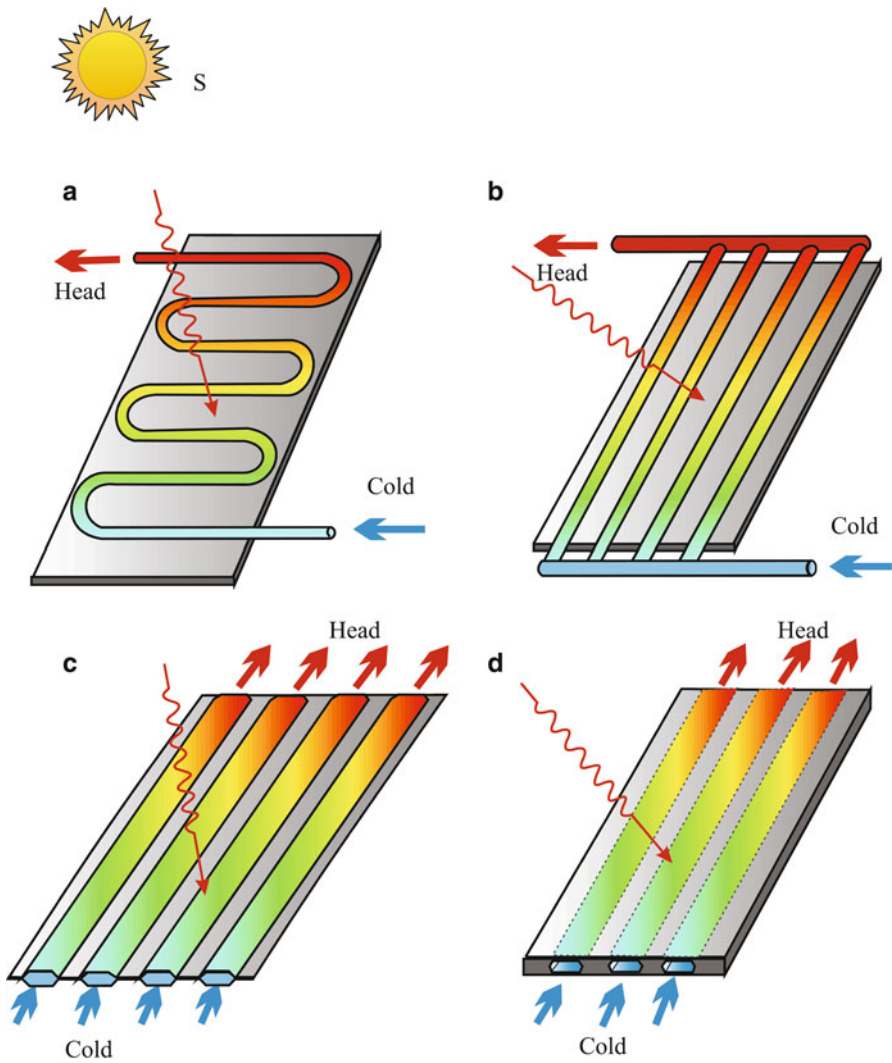


Fig. 3.16 Heat exchangers for solar collectors

increases and vapours move to the capacitor condenser – the end of pipe (6). Here vapours condense giving heat to water flowing through the pipe (7). The liquid from the condenser flows in the opposite direction through pipe (3). Vacuum tube solar collector contains several tubes connected in parallel and mounted into a common frame to form a register.

Disadvantages of vacuum solar collectors: they are about 1.5 times more expensive, have a greater mass; there is a risk of deterioration of tight connections that cannot be repaired under service conditions.

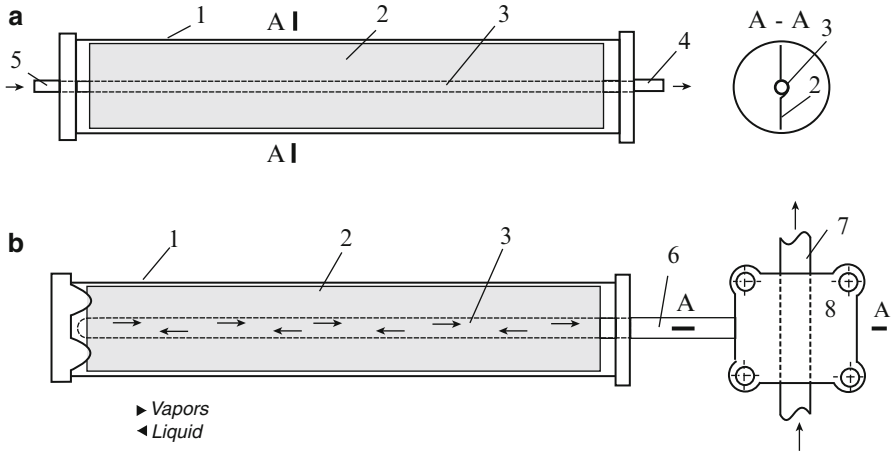


Fig. 3.17 Design of vacuum tubes

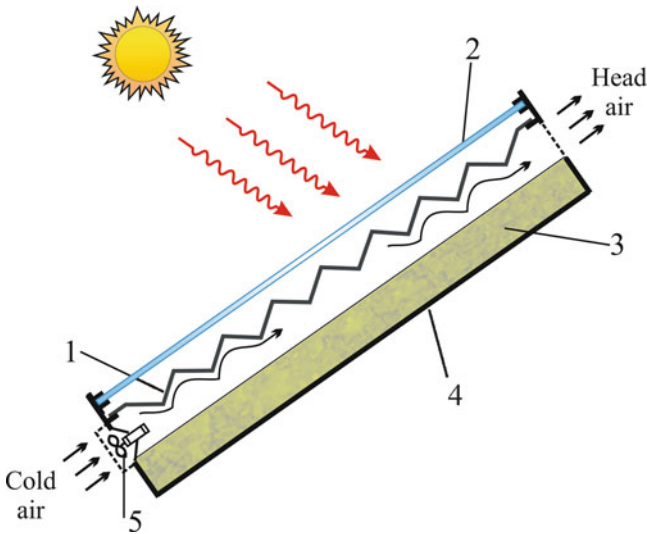


Fig. 3.18 Solar collector for air heating

Scheme design of air heating solar collector is similar to the water collector (see Fig. 3.18). Its main components are: absorbing surface (1), transparent area (2), the thermal insulation (3) and frame (4). Heat transfer takes place between AS and the airflow moving through the channel between TS and AS or between AS and thermal insulation layer, or both.

Air density is about 900 times smaller than that of water and a more intensive circulation of air is required. To this end, the fan (5) is used to transport cold air to AS and further to the consumer. Thermal conductivity of air is about 25 times

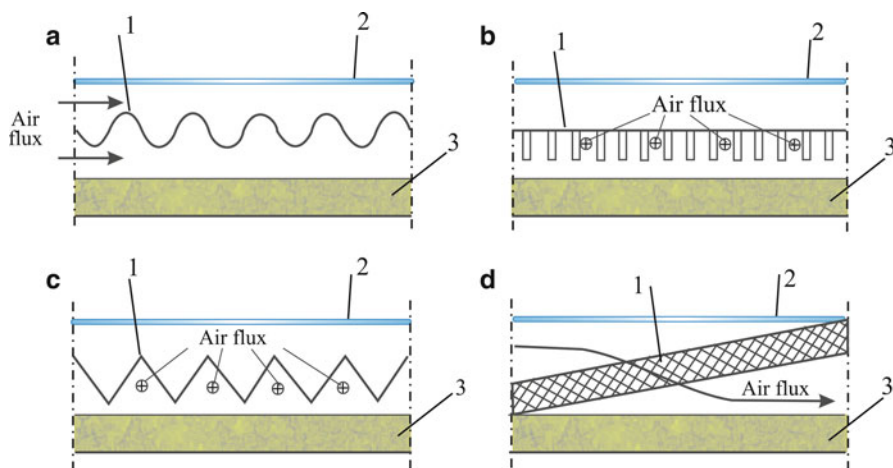


Fig. 3.19 Solar collectors for air heating: design of absorbing surfaces

smaller than that of water and it is necessary to substantially increase the contact area between TS and the airflow to achieve the same heat transfer. Air heating solar collector differs from that discussed above only by the design of absorbing surface 1.

In Figure 3.19 there are four design options of TS, whose major goal is to increase contact area between air and TS, creation of turbulent air movement and, consequently, increase of heat transfer efficiency:

- Wavy surface, air flow moves through both channels;
- The airflow moves through channels formed from metal plates welded to the rear of AS, forming a register (Fig. 3.19, airflow direction is perpendicular to the surface of the page);
- Differs from the previous version of the triangular shape of the channels;
- AS is composed of metal wire mesh or filled with granular material, through which air flows.

3.3.2.3 Thermal and Design Characteristics of the Solar Flat-Plate Collector

Standard flat-plate collector efficiency. Figure 3.20 presents a simplified energy balance of a standard flat-plate collector. Dimensions of the building elements are conventional. From short-wave direct and diffuse global solar radiation G , incident on the transparent area TS, an important part τG determined by the transparency coefficient τ , reaches the absorbing surface AS, where it is converted into heat. Transparent surface TS reflects radiation ρG into space and absorbs $\alpha_T G$, these values being quantitatively determined by reflectance ratio ρ and, respectively, by the material absorption coefficient α_T of material TS. Part of the radiation τG incident on the absorbing surface AS is reflected and the biggest part is converted into heat.

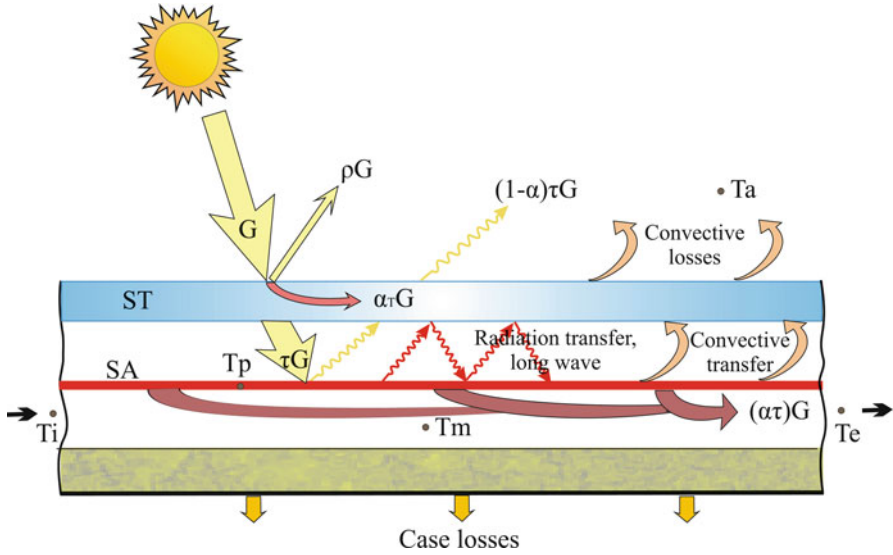


Fig. 3.20 Simplified energy balance of the solar flat-plate collector

It is obvious that for TS the sum of τ , ρ and α_T coefficients is:

$$\tau + \rho + \alpha_T = 1. \quad (3.26)$$

Absorbing surface AS absorbs solar radiation, temperature T_p increases to 40–100°C and AS will also radiate energy, but already in the long-wave infrared band, for which TS is opaque. Arriving to TS, this radiation is partially absorbed, heating the TS, and is partially reflected to the surface AS. Thus greenhouse effect is simulated by means of TS which prevents the emission into space of infrared radiation emitted by AS.

Efficiency: Efficiency of converting solar radiation into heat is determined by the absorption coefficient α of the surface AS. Only a fraction of global solar radiation G will turn into heat, due to material properties of transparent surface TS and of the absorbing surface AS:

$$P_{SA} = (\alpha\tau)G. \quad (3.27)$$

P_{SA} power must cover energy losses from the surface TS, which take place by convective transfer, as well as by casing losses. These losses are in the first approximation proportional to the temperature difference between T_p of AS and that of the environment T_a :

$$\Delta P = U_P(T_p - T_a), \quad (3.28)$$

where U_P is the total loss coefficient, $W/m^2 \cdot ^\circ C$, ranging from 1 to 30 $W/m^2 \cdot ^\circ C$.

Table 3.5 Characteristics of main flat-plate collector types

Collector type	$(\alpha\tau)$	Overall loss factor ($\text{W/m}^2\text{°C}$)	
		Usual interval	Average
Selective surface, void tubes, SS-V	0.7	2–3	2.5
Selective surface, glass sheet, SS-1	0.85	3–5	4.0
Black surface, two glass sheets, SN-2	0.75	4–6	5.0
Black surface, one glass sheet, SN-1	0.85	6–8	7.0
Without transparent surface, FST	0.95	15–30	20.0

Useful power generated by solar collectors is determined by the expression, known as Hottel-Whillier-Bliss (H-W-B)

$$P_U = (\alpha\tau)G - U_P(T_P - T_a) \quad (3.29)$$

and thermal efficiency

$$\eta = \frac{P_U}{G} = (\alpha\tau) - U_P \frac{T_P - T_a}{G}. \quad (3.30)$$

From the expression (3.30) follows:

- When $U_P = \text{const.}$ and $(\alpha\tau) = \text{const.}$, the efficiency decreases linearly depending on $(T_P - T_a)/G$;
- Maximal efficiency is when $T_P = T_a$ and it depends only on the optical properties of the TS and AS material;
- Global radiation G decrease leads to efficiency decrease.

Factor $(\alpha\tau)$ characterizing optical properties of TS-AS unit (transparent surface – absorbing surface), provides a classification of solar collectors in terms of efficiency and of overall loss coefficient U_P . Table 3.5 lists the main types of solar collectors, usual values of $(\alpha\tau)$ factor, and, overall loss coefficient, respectively. Figure 3.21 presents the evolution of efficiency in terms of temperature difference $T_a - T_P$. The calculation was performed using the expression (3.30) for mean overall loss coefficient and the value of global solar radiation $G = 800 \text{ W/m}^2$, and the temperature $T_a = 20^\circ\text{C}$.

Common collectors' characteristics: Evolution of efficiency from Fig. 3.21 and the characteristics listed in Table 3.5 provide information for comparative analysis of different flat-plate solar collectors' construction:

1. The characteristics of SN-1 collector with a black absorbing surface and a glass layer occupy an intermediate position. It is the most frequently used and in the above conditions it allows water heating up to 60°C temperature with efficiency between 45% and 50%. This type of collector is considered, usually, a reference one;
2. By excluding the transparent surface TS, the FTS collector is obtained, called **energy roof**, which increases the factor $(\alpha\tau)$, but simultaneously increases the

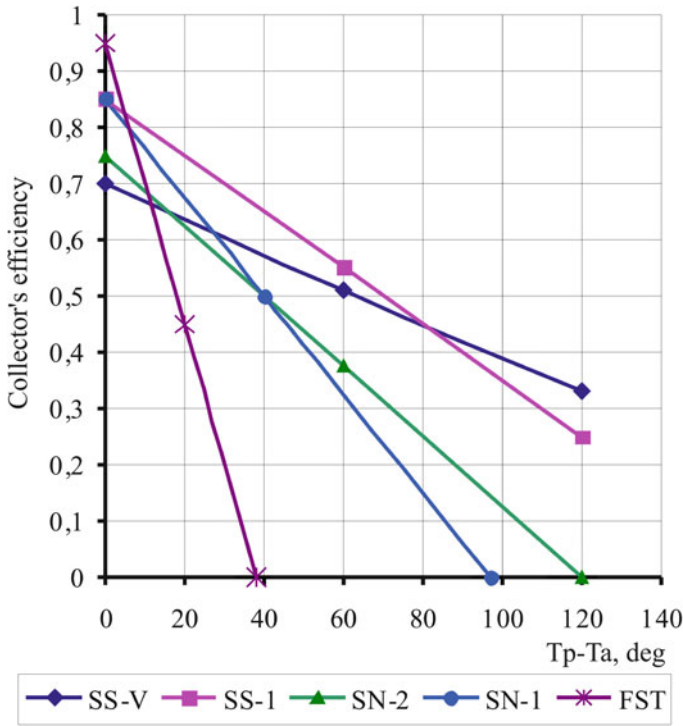


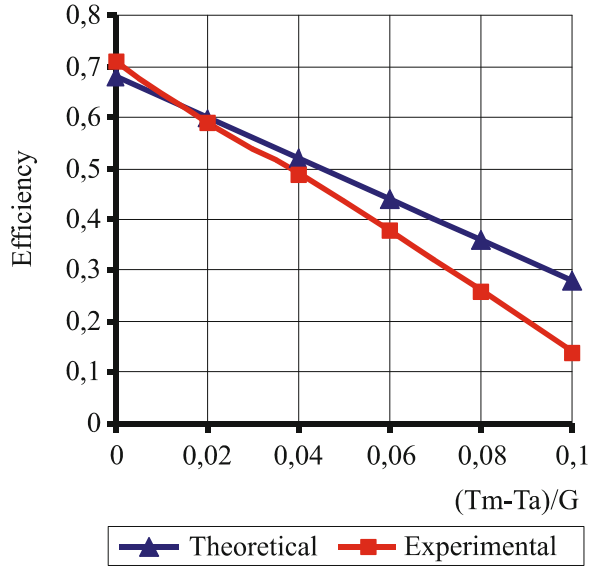
Fig. 3.21 Efficiency evolution of various types of solar collectors

overall loss coefficient U_p due to direct wind exposure and convective heat transfer enhancing. Provides air heating to 40–50°C with efficiency between 30% and 50%. It is commonly used for drying agricultural products (hay, grain, fruit, vegetables, etc.);

3. By installing two glass layers the collector SN-2 is obtained, which reduces the convective and radiative losses, but decreases the factor $(\alpha\tau)$ due to transparency diminution. In the usual $T_p - T_a$ temperature differences zone, between 30°C and 60°C, a significant increase of efficiency does not take place, and the collector is harder and more expensive in return.
4. Radiative losses can be significantly reduced in SS-1 collector with selective absorbing surface (next paragraph) and a single glass layer. Here convective losses are dominant;
5. A radical solution to minimize convective losses is to use vacuum tubes. It takes place in the selective surface SS-V collector. This type of collector allows water heating to temperatures above 100°C.

Irrigation factor, Equation H-W-B depending on the fluid temperature: In Eqs. 3.29 and 3.30 useful power delivered and efficiency are expressed in terms of the difference $(T_p - T_a)$ between temperature of the absorbing plate (surface),

Fig. 3.22 Efficiency of collector, type SS-1



and environmental temperature, respectively. In reality, the net output is lower and proportional to the difference $(T_m - T_a)$ between the average temperature of the heat delivering liquid $T_m = (T_i - T_e)/2$ and environmental temperature, where T_i and T_e (Fig. 3.20) are the fluid input- and output temperatures, respectively. Power or energy transmitted by the plate to heat delivering liquid depends on several factors:

- Its nature: water, air, antifreeze, etc.;
- Specific mass flow per unit area, kg/h m^2 ;
- Liquid specific heat, $\text{J/kg} \cdot ^\circ\text{C}$;
- Average temperature of the heat delivering liquid T_m .

To take into account the above stated, into efficiency Eq. 3.30 factor $F' < 1$ is inserted, known in English as *Heat Removal Factor*.

$$\eta = F' \left[(\alpha\tau) - U_P \frac{T_m - T_a}{G} \right] \quad (3.31)$$

or

$$\eta = \eta_0 - U_m \frac{T_m - T_a}{G}, \quad (3.32)$$

where $\eta_0 = F' \cdot (\alpha\tau)$, $U_m = F' U_P$.

Heat Removal Factor F' is of thermal nature and can be calculated prior, having as input data heat exchanger construction (Figs. 3.16, 3.17). These calculations are described in detail in [4]. For pipe-sheet heat exchanger (Fig. 3.16, b), the F' factor varies between 0,8 and 0,85, and for the plate-channel type (Fig. 3.16, d) it is equal to 0,98. Figure 3.22 presents SS-1 solar collector efficiency in terms

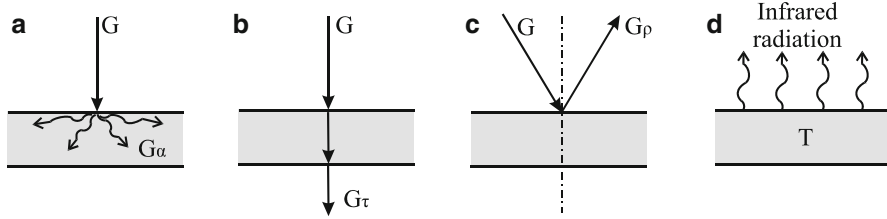


Fig. 3.23 Absorption (a), transmission (b) and reflection of short wave radiation (c). A body (surface) with temperature T is emitting long wave radiation into the space (d)

of $(T_m - T_a)/G$ calculated according to (3.31) ($F' = 0.8$) and the average efficiency obtained experimentally according to the American standard ASHRAE 93–73 [4]. There is a good approximation in the water temperatures between 30°C and 60°C and a relatively large deviation at temperatures above 60°C . For a properly designed and constructed collector type SN-1 or SS-1, the following efficiency average values are recommended for technical and economic calculations:

- Summer conditions – from 0.5 to 0.55;
- For the entire warm season (April to October) – from 0.40 to 0.45;
- Throughout the year – from 0.30 to 0.35.

3.3.2.4 Optical Properties of the Materials for Transparent Absorbing Surfaces

As outlined above, maximum efficiency of solar collector or factor $(\alpha\tau)$ depends only on the properties of materials used for the absorbing surface or plate AS, respectively, for the transparent area TS. The solar radiation entering any surface can be absorbed, transmitted through material or reflected (Fig. 3.23).

The concept of spectral absorption coefficient α_λ equal to the ratio of the wavelength λ radiation absorbed and radiation incident on the same wavelength is introduced. Coefficient α_λ represents a property of matter and does not depend on the radiation property, for example, on the incident radiation wavelength. It just shows what part will be absorbed by the interaction of respective electromagnetic radiation with the material (for solar installations – absorbing surface). Also, the concept of spectral transmittance coefficient τ_λ , and that of spectral reflection coefficient ρ_λ are introduced.

Energy conservation law requires that the sum of these coefficients is equal to 1:

$$\alpha_\lambda + \tau_\lambda + \rho_\lambda = 1. \quad (3.33)$$

The values of these coefficients are approximately constant in the range of the incidence angle θ variation between 0° and 60° and decreases sharply for angles greater than 70° .

Given that solar radiation has a broad spectrum of electromagnetic waves, the terms below are used for practical purposes, which reflect the interaction of the material and electromagnetic radiation throughout its range:

1. *Absorbance* α , defined as the ratio between the power of the absorbed- and incident solar radiation:

$$\alpha = \frac{G_{\alpha}}{G}; \quad (3.34)$$

2. *Transmittance* τ , defined as the ratio of radiated power transmitted through the respective material and the incident radiated power:

$$\tau = \frac{G_{\tau}}{G}; \quad (3.35)$$

3. *Reflectance* ρ , determined as the ratio of reflected radiated power to incident radiated power:

$$\rho = \frac{G_{\rho}}{G}. \quad (3.36)$$

Equation 3.34 can be written as follows:

$$\alpha = \frac{\int_0^{\infty} \alpha_{\lambda} G_{\lambda} d\lambda}{\int_0^{\infty} G_{\lambda} d\lambda}. \quad (3.37)$$

Similarly coefficients τ and ρ can be expressed. The relation (3.32) is also respected

$$\alpha + \tau + \rho = 1.$$

The coefficients α , τ and ρ characterize the behaviour of transparent or absorbing surface at solar radiation action, which represents a spectrum of *short waves* between 0.3 and 3 μm . They are also called *optical* or *solar* coefficients. At the same time, the respective area is heated and generates into space infrared radiation in the range between 3 and 20 μm . This process is characterized by spectral **emission** coefficient ε_{λ} , called *radiative* and defined as the ratio of delivered radiative power flux $W_{\varepsilon\lambda}$ with the wavelength λ and the flow of power delivered by an absolutely black body $W_{\lambda n}$ at the same wavelength λ and temperature T .

According to Kirchhoff's law for any wavelength λ and temperature T the following relationship occurs:

$$\alpha_{\lambda} = \varepsilon_{\lambda}, \quad (3.38)$$

in other words, a body with temperature T absorbs and emits the same amount of electromagnetic radiation with wavelength λ .

As defined above, the emission factor or *emittance* for the entire spectrum of radiation is determined similarly to the absorption α (v. 2.36):

$$\varepsilon = \frac{\int_0^{\infty} \varepsilon_{\lambda} W_{\varepsilon\lambda} d\lambda}{\int_0^{\infty} W_{\lambda n} d\lambda} = \frac{W_{\varepsilon}}{W_n}, \quad (3.39)$$

where W_{ε} , W_n is the flow of real power delivered by the body with temperature T , and, respectively, the flow of power delivered by an absolutely black body at the same temperature.

In accordance with expression (3.6), an absolutely black body of A area will emit an equal power flux $W_n = \sigma \cdot A \cdot T^4$ and, therefore, the flow of radiative losses will be:

$$W_{\varepsilon} = \varepsilon \cdot \sigma \cdot A \cdot T^4. \quad (3.40)$$

Absorbing surface materials: The ideal material has the following optical properties $\alpha = 1$, $\tau = \rho = 0$. It is obvious that such a material does not exist. Absorbing surface, being opaque, has transmittance τ equal to zero. The major part of solar radiation is absorbed and converted into heat and only a small fraction of solar radiation is reflected.

Table 3.6 shows absorption and emission characteristics collected from [4, 11, 12] for various materials and surfaces. The absorbance of material or the absorbing surface of solar radiation in the short wave range (0.3–3.0 μm) was noted with α_{short} , and $\varepsilon_{\text{long}}$ is emittance of the material or surface in the infrared wave range (bigger than 3.0 μm). We conclude that pure metals are not suitable for making absorbing surfaces. Also, aluminium is not recommendable because it may induce very fast electrical corrosion phenomena into the installation circuit. Steel plate covered with black paint has a satisfactory absorption, is cheap, but is not resistant to corrosion.

A special class is formed by the selective materials and surfaces possessing a high absorption coefficient for short waves, and, respectively, a lower emission coefficient for long waves. For these materials, the report $\alpha_{\text{short}}/\varepsilon_{\text{long}} \gg 1$.

Figure 3.24a, shows the spectral characteristics for various absorbing surfaces; and Fig. 3.24b, shows the explanation of the selective surface effect. In the spectral range between 0.3 and 3 μm absorbance and emittance of ideal selective surface is equal to 1, and in higher frequencies range over 3 μm – are zero.

Copper oxide (selective material) characteristic differs from the ideal one, but there was noticed a small value of emittance over the spectrum zone bigger than 10 μm . Selective surface absorbs approximately 85–95% of solar radiation (short wave), which turns into heat and is transmitted to the copper plate. However, both copper and copper oxide emit into space only about 10% of radiation that could

Table 3.6 Absorbance and emittance of some materials and absorbing surfaces

Type of material or absorbing surface	Absorbance, α_{short} , short wave	Emittance, $\varepsilon_{\text{long}}$, infrared waves	Ratio $\alpha_{\text{short}}/\varepsilon_{\text{long}}$
<i>Traditional materials</i>			
Pure iron	0.44	0.11	4.0
Pure aluminium	0.10	0.10	1.0
Polished copper	0.35	0.08	8.8
Oxidized steel sheet	0.74	0.82	0.90
Steel sheet plated with black paint	0.95	0.95	1.0
Graphite (black lead)	0.78	0.41	1.90
Carbon black	0.96	0.89	1.08
White paint	0.12–0.18	0.93	0.13–0.19
<i>Selective materials and surfaces</i>			
Black chromium on a nickel surface	0.95	0.09	10.7
Porous ceramic son a steel surface	0.96	0.16	6.0
Black nickel oxide (green oxide) on an aluminium surface	0.85–0.93	0.06–0.10	14.5–15.5
Copper oxide, Cu_2O , on a copper surface	0.90	0.16	6.0

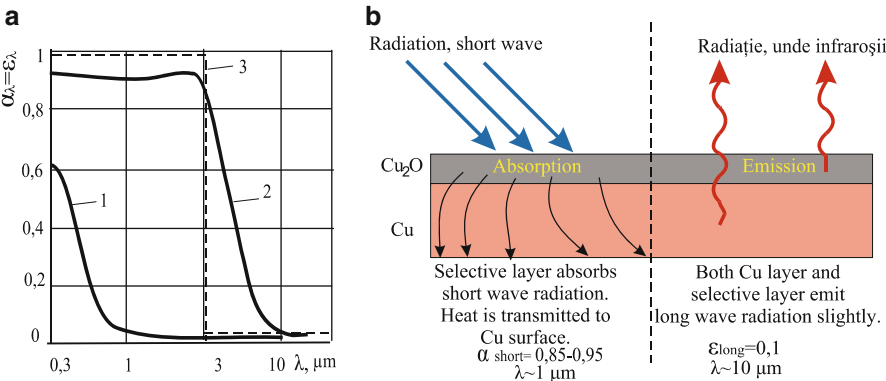


Fig. 3.24 Spectral characteristics of different materials (a) and explanation of the selective surface effect (b)

be emitted by an absolutely black body at the same temperature. In other words, selective surface creates the same greenhouse effect as a glass layer covering the solar collector surface. This explains the solar collector efficiency increase with selective surface (Fig. 3.21).

Transparent surface materials: Ideal transparent material transmittance is $\tau = 1$, its absorbance is $\alpha = 0$ and reflectance $\rho = 0$. Characteristics of real materials which can be used to manufacture transparent surfaces are shown in Table 3.7. The best quality material for transparent surface is low iron oxide glass or ordinary

Table 3.7 Characteristics of transparent materials

Type of material	Transmittance (τ)	Absorbance (α)	Reflectance (ρ)
Window glass (6 mm)	0.80	0.12	0.08
Float glass (4 mm)	0.87	0.07	0.06
Glass with reduced content of iron rust	0.91	0.01	0.08
Polycarbonate	0.70	–	–
Polyethylene film	0.82	–	–
Plexiglass (acrylic glass) (3 mm)	0.80	–	–
Tedlar	0.88	–	–

glass. Glass transmittance drops abruptly for infrared radiation ($\lambda > 3.0 \mu\text{m}$), and, therefore is opaque for radiation emitted by the absorbing surface, thus the greenhouse effect taking place.

Plastics can also be used. They are lighter and cheaper than glass, but age quickly under the action of ultraviolet rays and hence must be replaced periodically (after every 6–12 months). Another plastics disadvantage is low radiative properties. Thus, the polyethylene has an infrared radiation transparency coefficient of 0.8 and therefore will not provide adequate greenhouse effect.

The characteristics shown in Table 3.7 are presented for Sunbeam incidence angles $\theta < 40^\circ$ – typical angles for most collectors. Reflectance rises sharply and transmittance reduces for incidence angles bigger than 60° .

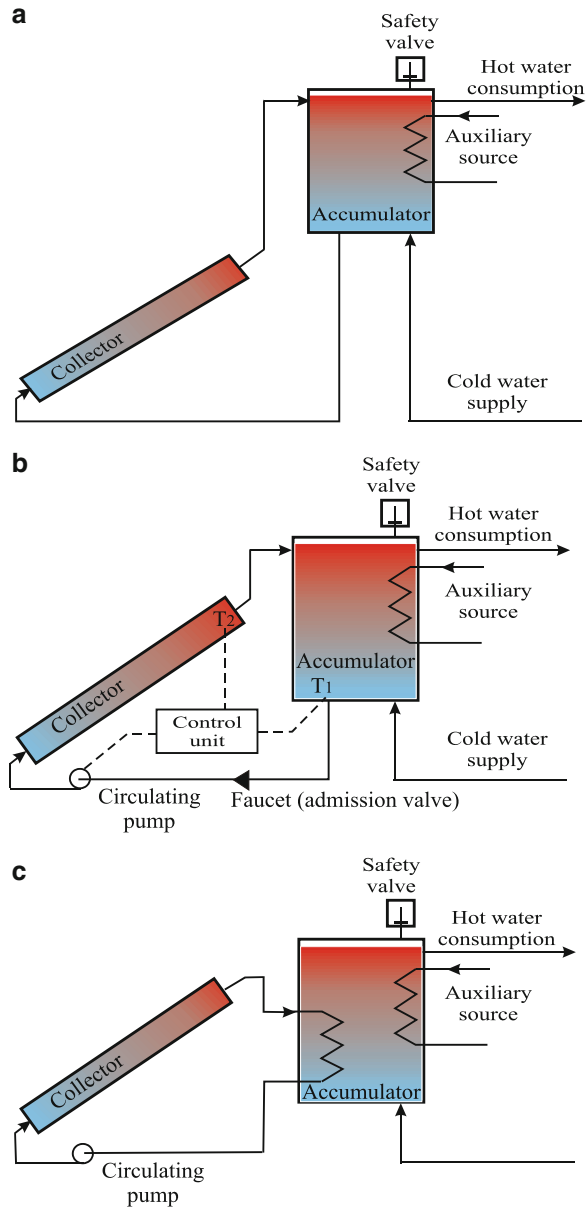
3.3.2.5 Schematic Diagram of Solar Water Heating Systems

The most widespread solar water heating systems (SWHS) are shown in Fig. 3.25. The basic components of SWHS are: flat solar collector, storage tank (water reservoir), heat exchanger, circulating pump, auxiliary energy source. The difference of the presented diagrams consists in the interconnection and structural arrangement.

SWHS with natural circulation: Figure 3.25a shows a SWHS with natural circulation. To ensure a steady water circulation the storage tank should be mounted higher than the collector. In both components, in the collector and in the water reservoir a difference of temperatures in their upper and lower parts is settled, that leads to a difference of density between the water layers (hot water is easier than cold water) and finally to a pressure difference that ensures water circulation. Pressure difference depends on the temperature difference and thus the water flow in the system depends on the useful power captured by the collector that causes this temperature difference. In these circumstances, SWHS with natural circulation are self-adjustable – the increase in the captured output leads to the increase of the water flow that circulates in the system.

Theoretical and experimental studies carried out in the 70s of the last century have demonstrated [4] that for a wide range of SWHS with natural circulation

Fig. 3.25 Schematic diagram of solar systems for water heating: (a) with gravity (natural) circulation; (b) with pump circulation; (c) with two profiles



the temperature difference of water input and output from the collector is about 10°C and remains constant during the day (see Fig. 3.26). Specific water discharge is $50\text{--}60\text{ l/m}^2\text{h}$. For example, in a SWHS with the collector's surface 4 m^2 water discharge is about 200 l per hour. If storage tank volume is $200\text{--}300\text{ l}$ then during a day this volume of water will circulate in the system several times, heating. It is

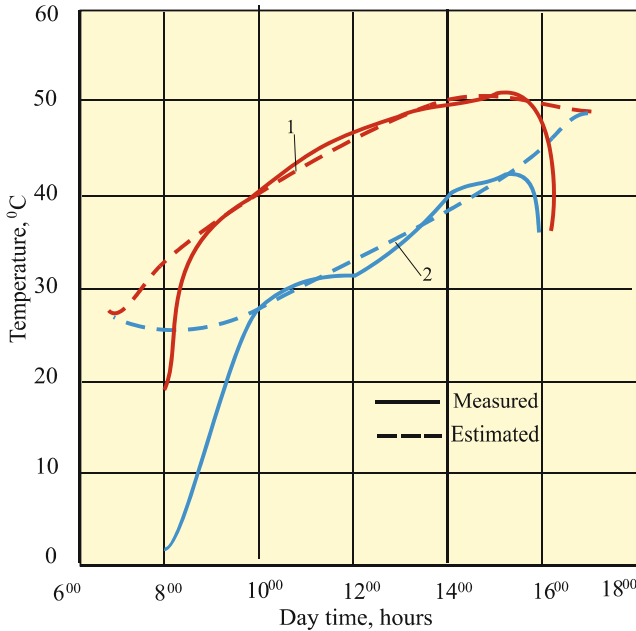


Fig. 3.26 Variation of water temperature during the day: 1 – at outlet; 2 – at inlet

obvious that the temperature difference between the upper and lower layers water in the tank will be minimum and water circulation will stop (see Fig. 3.26). SWHS with natural circulation is widely used in Israel, Australia, California and Florida in the USA where there is no danger of frost. The construction of this system is simpler, does not demand additional cost and is designed to heat water at the temperature of 65°C . In Moldova, SWHS with natural circulation can be operated April to September. To avoid deterioration of collector it is recommended to empty it from water in the cold period of the year. The auxiliary electrical energy source or the source based on natural gas use allows coverage of hot water over consumption. It can be paralleled with the solar collector (as shown in Fig. 3.25a or in series). In the last case, SWHS operates as preheater. It should be mentioned that SWHS with natural circulation will operate with higher efficiency if main hot water consumption will occur in the morning hours. Or, the water reservoir must be filled with cold water before maximum solar radiation occurs.

SWHS with pump circulation: SWHS with pump circulation is shown in Fig. 3.25b. The circulating pump will depend on the temperature difference T_2 in the upper part of the collector and temperature T_1 in the lower part of the reservoir. Temperature is controlled by a balanced relay and the pump will operate only when the temperature difference will overrun the predetermined value. To exclude the reverse circulation of water at night a unidirectional valve is envisaged.

In the regions with danger of frost the diagram of SWHS will be modified and will have two circulation contours. The first contour (Fig. 3.25c) comprises

a collector, a circulating pump and a heat exchanger, and it is filled with antifreeze solution. The second contour is the hot water circuit itself. Heat transfer between the first and the second contours is done via a liquid-liquid heat exchanger (see the coil in the storage tank).

This diagram is widely spread in the countries of Central and Northern Europe and in the North America. A standard SWHS comprises 2–3 collectors (their size is 1×2 m), water reservoir volume is 200–400 l, specific water discharge is 50–60 l/m²h. Solar collector is made of single-layer glass, the absorbing surface is selective, and in some cases is a black surface.

An important role in SWHS manufacturing belongs to the degree of water column (water height) layering in the reservoir. The higher the degree of layering, the bigger the solar cut fraction in covering annual hot water supply. In this context, it is rational to decrease the specific discharge. The studies carried out in Sweden in the 90s of the last century showed that the optimal discharge (output) in a SWHS with pump circulation is 7–20 l/m²h.

3.3.2.6 Practical Aspects of Solar Water Heating Systems

Transparent surface (TS) and absorbing plate (AS): The importance of optical characteristics of materials for manufacturing transparent surfaces and absorbing plates was underlined in Sect. 3.3.2.4. Properties ($\tau\alpha$) and ε have a direct impact on thermal performances of the solar collector. The selected materials should have steady properties in time as their degradation can affect long-term properties of the collector. The surface of the absorbing plate should resist at maximum possible temperatures in the period of exploitation. This can be determined easily from the Eq. 3.30 under the condition that useful power $Q_u = \eta G$ is equal to zero (there is no water circulation). The fluid temperature T_m will equal the plate temperature. Obviously, the selective material or the applied paint should resist to these temperatures. In the case of transparent surfaces there is danger of their destruction by hailstones. On the basis of some real experiments it was concluded that the risk of destruction of the collector covered with tempered 3 mm glass is to be neglected. Thus, in 1979 in Colorado, USA, due to a storm lasting several minutes the size of hailstones was 2–3 cm in diameter, then after a small period of silence, for 1–2 min, the size of falling hailstones was 3–10 cm in diameter. One thousand and ten solar collectors, mounted under angles between 32° and 56°, were exposed to hailstones and the glass was broken in 11 collectors only [4].

The combination of glass with the casing should be done without edges or fins that are pointed out above the transparent surface. This would facilitate water flow and snow sliding from the surface of the collector.

Heat insulation: Transparent surface (glass) and the air case between AS and TS have the role of heat insulation in the frontal part of the collector. The air case should be within 25 and 40 mm. The thickness 28 mm is considered optimum. The other sides of the collector (the underside and the lateral sides) should be isolated

with a 5–10 cm layer of fibre glass or other insulating material with similar heat insulation parameters. Fibre glass has the following advantages:

- Is relatively cheap;
- Has excellent insulating properties ($\lambda = 0.05\text{--}0.06 \text{ W/m K}$);
- Is temperature resistant, over 100°C ;
- Has very small specific gravity (unit/volume weight) ($\rho = 150\text{--}200 \text{ kg/m}^3$).

A disadvantage of fibre glass is loss of insulating features if it becomes moist. It is recommended to use panels of fibre glass and thus settling will be avoided at inclined placement of the solar collector.

A reasonable solution related to cost-quality can be heat insulation combined with a 4 cm fibre glass panel and with another 3 cm panel made of polystyrene expandant. Fibre glass is more resistant to higher temperatures, and is placed immediately after the absorbing plate, but polystyrene is placed after the fibre glass panel. In its turn, polystyrene is more water resistant. To improve heat insulation of the collector, it is recommended to introduce a thin aluminium sheet between the insulation and the absorbing plate. The sheet will have the role of a screen to infrared radiation that will be reflected to the absorbing plate. An air case between the absorbing plate and the sheet will have the role of additional heat insulator.

Collector pressurization: To prevent water and dust intrusion into collector, it is necessary to pack it. In conditions of cloudy sky water vapours condense on the internal surface of glass that will lead to decreasing its transparency and efficiency. At next starting of the collector, condensation will disappear only when the glass will become sufficiently warm for its damping. Thus, the collector, which internal air is damp, will start operation later and stop it earlier. If the collector is not packed the dust will intrude into it and will deposit on the interior side of glass and on the transparent plate. If economically it is difficult to perform perfect packing then it is recommended to have internal ventilation of the collector. Aiming at this, several holes (2–3 mm diameter) are made between TS and AS that are sheltered from rain.

Casing: It supports the unit and ensures collector's pressurization. The mostly recommended material is the anodized aluminium angle and zinc steel sheets. The structure of casing does not need high mechanical strength. Usually the collectors are placed on house roofs (Fig. 3.27) or are retained by a support made of steel angle profile. This support will take over wind stresses too.

The casing is simple in construction and presents a box with flat or undulated ground (for a higher rigidity) and four sides. The height of sides should correspond to the mounting requirements for heat insulation, transparent and absorbing surfaces and an air case, a total height of 10–15 cm. It is important that the casing and collector's weight is small in order to ease its mounting.

Collectors' mounting will be in series or parallel (Fig. 3.28). At series connection water flows consecutively through collectors and heats more and more. The collectors will operate under various temperatures, with a decreasing efficiency from input to output. Hydraulic resistance is increasing. Due to this, it is recommended for pump circulation systems.



Fig. 3.27 An example of solar water heating system: solar collectors are integrated in the roof of the house directed to the south

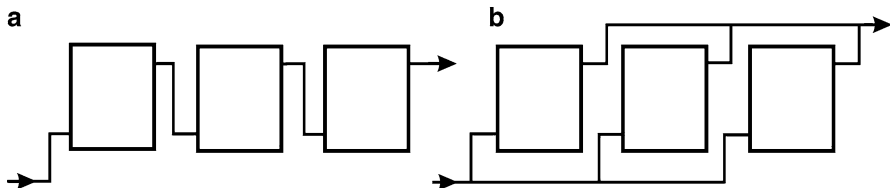


Fig. 3.28 Connection of solar collectors, in series (a) and parallel (b)

When mounted in parallel, each solar collector will ensure only a part of the discharge and will have about the same temperature. Hydraulic resistance decreases and the system can operate under natural circulation (thermo siphon). Also hybrid systems with series/parallel or parallel/series connection might be applied.

An autonomous solar water heating system is shown in Fig. 3.29. Its solar collectors are mounted on metallic supports on the roof. Solar collectors are fixed and oriented to Sun at maximum position of solar radiation.

3.3.2.7 Dimensioning of a Solar Water Heating System

Previously it was stated that SWHS efficiency decreases together with the increase of temperature between the absorbing plate and the environment. It is important to



Fig. 3.29 Solar system for water heating

estimate correctly the dimension of solar collector's surface and the volume of water reservoir depending on the:

- Available overall radiation on the collector's surface;
- Daily hot water consumption and temperature;
- Distribution of water consumption over the day.

Further on, a simple method for dimensioning is described. This method allows preliminary SWHS estimation, in particular, at the first stage of designing solar energy systems, inclusive feasibility studies.

SWHS diagram is shown in Fig. 3.25a. It has a single contour with natural circulation. The dimensioning estimates refer to the following sizes:

- Optimum angle of dip of solar collectors for the given period: March to October, central regions, e.g. Moldova;
- Average global radiation for the given period incident on collector's surface and monthly average global radiation;
- Daily consumption of hot water and its distribution for 24 h;
- Solar collector surface;
- Volume of hot water storage reservoir;
- Minimum water temperature per month with smaller solar radiation.

The optimum angle of dip of solar collectors is chosen so as in March and October more solar energy is radiated to the collector's surface, and care is taken that in summer this quantity of energy does not decrease under the required level.

Overall average radiation incident on the collector's plane: Average daily values of direct and diffuse solar radiation on a horizontal surface for the period from March to October are taken from local characteristics. Diffuse radiation is determined as

Table 3.8 Overall radiation at the collector surface for the studied period

Month		III	IV	V	VI	VII	VIII	IX	X
R_b	–	1.57	1.15	0.93	0.85	0.88	1.06	1.38	1.94
B	$\text{MJ/m}^2 \cdot \text{zi}$	4.22	7.34	10.26	13.03	12.55	11.24	8.51	4.78
D	$\text{MJ/m}^2 \cdot \text{zi}$	5.57	7.98	9.32	10.05	9.55	8.06	6.14	4.3
$B_\beta = R_b B$	$\text{MJ/m}^2 \cdot \text{zi}$	6.63	8.44	9.54	11.07	11.04	11.91	11.74	9.27
$D_\beta = 1/2$ ($1 + \cos\beta$)	$\text{MJ/m}^2 \cdot \text{zi}$	4.86	6.96	8.13	8.76	8.33	7.03	5.35	3.75
$G_\beta = B_\beta + D_\beta$	$\text{MJ/m}^2 \cdot \text{zi}$	11.49	15.4	17.67	19.83	19.37	18.94	17.09	13.02
	$\text{kWh/m}^2 \cdot \text{zi}$	3.20	4.31	4.95	5.55	5.42	5.30	4.79	3.64

Table 3.9 Twenty-four hours consumption of home hot water

Hour	Consumption (%)	Hour	Consumption (%)	Hour	Consumption (%)
0–1	0.0	8–9	4.6	16–17	4.2
1–2	0.0	9–10	4.4	17–18	4.5
2–3	0.0	10–11	3.9	18–19	5.7
3–4	0.0	11–12	4.0	19–20	7.8
4–5	0.0	12–13	4.6	20–21	9.1
5–6	3.0	13–14	4.6	21–22	9.1
6–7	5.2	14–15	4.6	22–23	6.5
7–8	5.4	15–16	4.0	23–24	4.7

Table 3.10 Daily distribution of hot water consumption, $C(t)$

Hour		0	4	6	8	10	12	14	16	18	20	22	24
C(t)	%	0.0	0.0	3.0	13.6	22.6	30.5	39.7	48.3	57.0	70.5	88.7	99.9
	l	0.0	0.0	6.0	27.2	45.2	61.0	79.4	96.6	114.0	141.0	177.4	200.0

the difference between the overall and direct radiation. Global radiation on the collector's surface is determined from the expression (3.25), neglecting the reflected component:

$$G_\beta = R_b \cdot B + \frac{1}{2} (1 + \cos\beta) D. \quad (3.41)$$

The obtained results are included in Table 3.8.

Daily consumption of hot water and its distribution for 24 h: Daily demand for hot water and its distribution for 24 h depend, to a great extent, on the consumer's specific characteristic measure. It is different for houses and industrial buildings. Assuming as consumer a family of four persons, the specific consumption q is 50 l/day per capita at the temperature 55°C. The distribution of water consumption for 24 h is shown in Table 3.9 [13].

The data in Table 3.9 and the daily consumption of 450 = 200 l/day defines the distribution of hot water consumption $C(t)$ during the day by summing the values for each hour. The results are introduced in Table 3.10, graphic presentation is given in Fig. 3.30. The same graph shows cumulative production of hot water from 7³⁰ to 18⁰⁰.

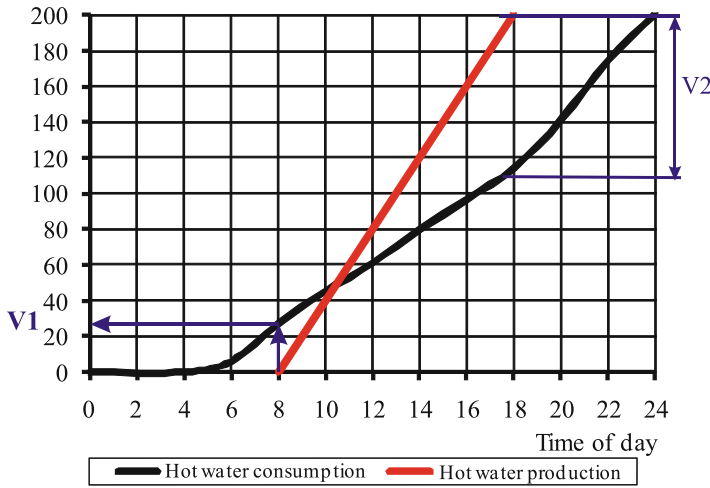


Fig. 3.30 Explanation of hot-water tank volume determination

Solar collector surface: The energy demanded to heat the daily water volume $C_z = 200$ l from 15°C to 55°C is estimated:

$$E_{nec.} = C_z \cdot c_{apei} (t_{cald\tilde{a}} - t_{rece}) = 200 \cdot 4.173 \cdot 10^3 \cdot 40 = 33.39 \text{ MJ/day}$$

where $c_{water} = 4.173 \cdot 10^3 \text{ J/}^\circ\text{C kg}$ shows the water specific heat.

Capture surface of the solar collector:

$$S_{col} = \frac{E_{nec}}{\eta_{col} \cdot G_{\beta med}} = \frac{33.39}{0.45 \cdot 16.6} = 4.5 \text{ m}^2,$$

where

η_{col} is collector average efficiency for the period of operation;

$G_{\beta med}$ – daily global solar radiation determined as the average for the period from March to October (see data in Table 3.8)

Volume of hot water storage tanks: Figure 3.30 shows that the storage tank should supply the hot water production deficit from 5 to 8 o'clock in the morning, and from 18 to 24 o'clock in the evening. Thus, the storage tank volume is:

$$V_a = V_1 + V_2 = 30 + 90 = 120 \text{ l.}$$

The temperature of hot water in March when solar radiation is the smallest:

$$t_{cald\tilde{a}} = t_{rece} + \frac{C_{\beta}^{III} \cdot S_{col} \cdot \eta_{col}}{C_z \cdot c_{apei}} = 10 + \frac{11.69 \cdot 10^6 \cdot 4.5 \cdot 0.45}{200 \cdot 4.173 \cdot 10^3} = 38.4^\circ\text{C}.$$

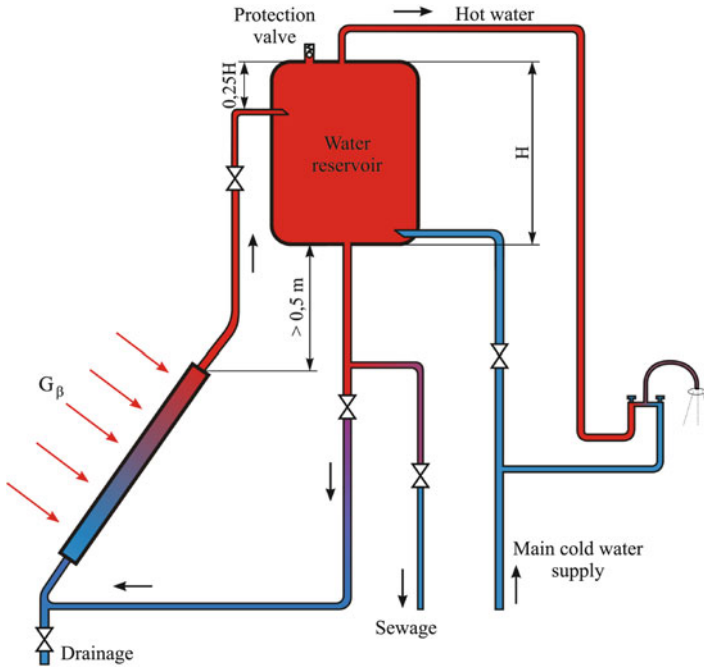


Fig. 3.31 Schematic diagram of a SWHS with natural circulation supplied with cold water from the main apeduct

So, one can see that in March a comfortable temperature of hot water for residential purposes is also supplied. Figure 3.31 shows the diagram of SHWS supplied with cold water from the supply main. In this case the water tank and the solar collector should resist to the main water pressure. If admissible pressure is overrun, the water tank is endowed with a protection valve. To ensure a good layering of water in the tank, hot water is injected to the upper part, and cold water to the lower part of the tank. The system described in Fig. 3.31 can be produced on the basis of the solar collectors manufactured at Incomaș-S.A. enterprise (Chișinău). The collector surface is 2.2 m^2 . Two collectors connected in parallel are necessary.

Quantity of thermal energy produced from March to October is determined from the expression:

$$E_{III-X} = N_z \cdot G_{\beta med} \cdot S_{col} \cdot \eta_{col} = 245 \cdot 16,6 \cdot 4,4 \cdot 0,45$$

$$= 8053 \text{ Mj} \quad \text{Or about 2 Gcal.}$$

3.3.3 *Systems for Solar Thermal Energy Conversion into Electrical Energy by Combining the Greenhouse Effect and Air Pressure Difference*

3.3.3.1 Brief History

In 1903, for the first time, Isidoro Cabanyes, a Spanish colonel, proposed a solar energy tower in the journal *La energia electrica* [14]. The solar tower with air currents has three main components: the solar collector, the tower and the wind turbine. One of the first descriptions of the solar energy tower was published in 1931 by Hanns Gunther, a German author [15]. Since 1975, Robert E. Lucier obtained several inventions for the electric generator with solar tower. From 1978 to 1981 these patents were valued in Australia, Canada [16], Israel and the USA. For the first time, solar energy came into the attention of society after the energy crisis of the 70s in the last century, on large scale.

In 1972 an operational model of small dimension thermal solar tower was developed under the supervision of engineer Jorg Schlaich, of German origin, in Manzanares, Ciudad Real, and located 150 km to the south from Madrid, Spain. The project was financed by the German Government [17–21]. The tower was 195 m high, and its diameter was 10 m. It had a collecting surface (greenhouse) of 46,000 m² (diameter – 244 m). This pilot-plant operated successfully about 8 years. Some experiments have been carried out [22, 23] and then it was closed up in 1989. Solar towers were advertised by an Australian TV programme *After 2000* in 1984, under the aspect of their adaptability for electrical energy generation in the under populated regions of Australia with no impact on animal breeding.

Haaf presented the testing results and described theoretically the solar tower prototype from Manzanares, Spain [17, 18]. Transferability of the obtained results in Manzanares was discussed by Schlaich, etc. (1990). In 1997 Kreetz has introduced the concept of water tank use that is mounted under the roof for heat collecting. Gannon and Backström have presented the analysis of solar tower thermodynamic cycle and the analysis of turbine characteristics, as well, in 2000 [19, 24]. Ruprecht [25] and others have described the results of dynamic design of the fluid and turbine for a 200 MW solar tower in 2003. Serag-Eldin MA (2004) [26] Weinrebe, G. (2000) [14, 26] have performed ample computer simulation of the air currents in the solar tower. El-Haroun AA (2002) [25] researched air velocity at tower output. Thermal and technical analysis was calculated computer assisted (described by Dos Santos Bernardes et al. in 2003) [4, 27]. A similar solar tower is developed recently in Australia, where conditions are favourable for such solar energy units, like: high level of solar radiation, vast available areas, demanded for electricity generation increase and existence of a governmental body – Mandatory Renewable Energy Target (MRET), that has demanded 9,500 GWh of renewable energy in 2010–2020 [17].

Economic estimations based on the experience and knowledge have demonstrated that large solar towers (≥ 100 MW) are capable to generate electrical energy

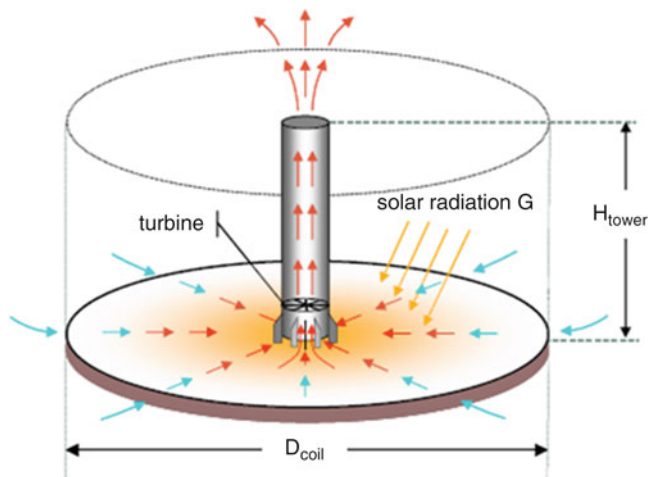


Fig. 3.32 Operation principle of solar tower

at the same cost as energy produced by conventional energy units [28–30]. In future, solar towers will contribute to low cost and environment friendly electrical energy generation in Sunny regions.

3.3.3.2 Solar Tower with Collector and Air Turbine: Theoretical Issues

Solar towers are solar thermal plants that use the combination of solar collector greenhouse effect and the pressure difference in the tower for generating convective air currents that drive the turbine to produce electricity. The main components of a solar tower are: air collector, tower (furnace) and the wind turbine.

These systems are destined for power scale applications ≥ 100 MW. The operating principle is shown in Fig. 3.32 [20]. The air heated by direct and diffuse solar radiation through a transparent circular shelter, open at periphery: the shelter and the natural soil form a solar collector. A tower with large entrance at its basis is placed in the middle of the shelter. As warm air is easier than the cold air, pressure difference occurs in the tower.

Thus, solar radiation is the reason of a constant pressure drop in the tower. Continuous operation for 24 h can be ensured by placing the tubes or tanks filled with water under the roof. Heat accumulated during the day is delivered during the night. The energy contained in the air flow created by the pressure difference is converted into mechanical energy through one or more turbines installed in the base of tower.

Next, the fundamental relations and influence of the basic parameters on the quantity of energy are presented in a simplified form. Generally speaking, the output

power P of a solar tower can be calculated as input power Q multiplied by the efficiencies of the collector, the tower and the turbine:

$$P = Q_{soil} \cdot \eta_{col} \cdot \eta_{tower} \cdot \eta_{turbine} = Q_{soil} \cdot \eta_{plant}. \quad (3.42)$$

Solar energy input into the system can be represented as the product of horizontal global radiation G_o and the collector's surface A_{col} :

$$Q_{soil} = G_o \cdot A_{col} \quad (3.43)$$

The tower transforms the warm currents produced by the collector into kinetic energy (convection currents) and the pressure action on the turbine. This difference in air density caused by temperature rise in the collector, works as a driving force. The column of warm air from the tower is connected with the lower atmosphere at the base (entry into the collector) and the atmosphere at the top of the tower, thereby creating a lifting force. Pressure difference ΔP_{sum} is produced between the base of the tower (collector's inlet) and the environment (tower's outlet):

$$\Delta P_{sum} = g \int_0^{H_{tower}} (\rho_0 - \rho_{tower}) dH_{tower}. \quad (3.44)$$

This difference of pressure ΔP_{sum} increases together with the tower height. The difference of pressure ΔP_{sum} can be divided as the static component and the dynamic component, neglecting the friction losses:

$$\Delta p_{sum} = \Delta p_s + \Delta p_d, \quad (3.45)$$

where:

$$\Delta p_s = P_a - P_{tower},$$

where:

P_a is the atmospheric pressure (at collector's inlet)

P_{sum} – pressure at tower outlet.

The difference of static pressure reacts on the turbine, and the dynamic component describes the kinetic energy of air currents. For a total difference of pressure and the volume of air currents when $\Delta P_s = 0$, power P_{sum} contained in the currents is:

$$P_{sum} = \Delta P_{sum} \cdot v_{tower,max} \cdot A_{col}. \quad (3.46)$$

Efficiency of the solar tower can be defined from the relation:

$$\eta = \frac{P}{Q_{sol}}. \quad (3.47)$$

Splitting the difference of pressures in static and dynamic components depends on the energy taken from the turbine. In the case of the tower without the turbine,

maximum speed of air currents is reached, and all pressure difference is used to accelerate the air and is converted into kinetic energy:

$$P_{sum} = \frac{mv_{tower\ max.}^2}{2}. \quad (3.48)$$

Using Boussinesq approximation, the speed achieved by convection currents can be expressed as:

$$v_{tower\ max.} = \sqrt{2gH_{tower} \frac{\Delta T}{T_o}}, \quad (3.49)$$

where ΔT is the temperature increase between the environment and the collector's outlet.

Efficiency of the solar tower will be defined from the relation:

$$\eta = \frac{g \cdot H_{turn}}{c_p T_o}. \quad (3.50)$$

where c_p is specific heat at constant pressure, $J\ kg^{-1}\ K^{-1}$.

This simplified representation explains one of the basic characteristics of the solar tower – solar tower efficiency depends on its height. For the 1,000 m height, the deviation from the exact solution due to the Boussinesq approximation is to be neglected. Using Eqs. 3.42, 3.43 and 3.50 it can be defined that the generated power is proportional to the collector's area and the tower height. Since the generated electricity is proportional to the volume of the tower's height and collector's area, the same power can be generated by a tower with a bigger diameter and small collector or vice versa. This refers to the operation of the solar tower during the day. But what happens at night? For the tower to operate 24 h out of 24 the water tanks with the black surface are installed on the ground collector. How these tanks operate? The tanks are sealed so that evaporation does not occur (Fig. 3.33) [20]. The volume of water in the reservoirs is calculated so as to correspond to a layer of water with the depth equivalent to 5–20 cm depending on the expected power characteristics (Fig. 3.34) [20]. At night, when the air in the collector is cooler, the water tanks deliver the accumulated heat. Heat capacity of water is approximately five times higher than that of the soil.

Solar tower does not convert the total amount of solar energy into electric energy. Relatively low conversion rate of solar tower is balanced by investment costs reduced to $1\ m^2$ of the collector [31]. According to the calculation, a solar thermal power plant (solar tower) with 200 MW capacity requires a collector with a 7 km diameter (total area about $38\ km^2$) and a tower at 1,000 m height [32].

Solar tower performance can be degraded by such factors as atmospheric winds [32] or by the brake induced by the arms used as tower carriers [32]. Another factor is the reflection of Sunlight by the material of the roof. The diagram (Fig. 3.35) shows that the solar beam PO breaks in point O the interface between

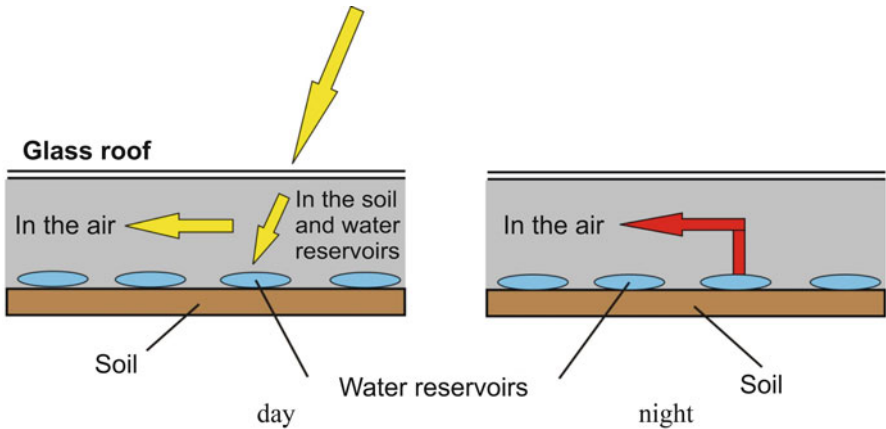


Fig. 3.33 Thermal energy storage in water-filled pipes

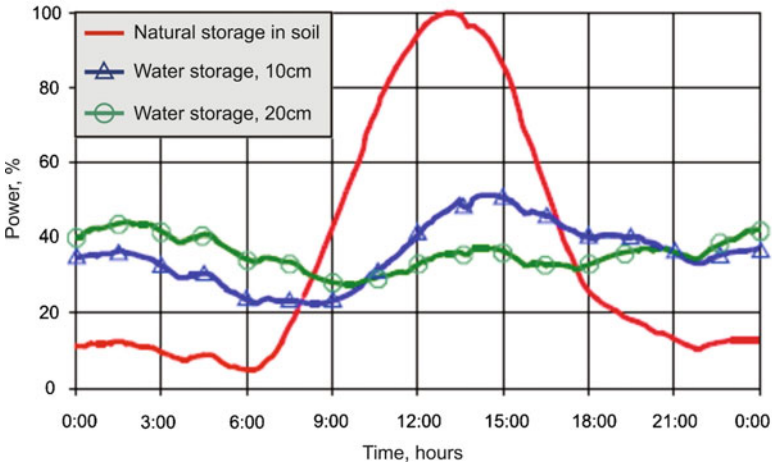


Fig. 3.34 Effect of heating storage in the collector, using waterfilled black surface storage tanks (simulated by Kreetz, 1997)

two environments with refractive indices n_1 and n_2 . Some of the rays (OQ) are reflected, and some (OS) are refracted. Angles between the rays (incident, reflected and refracted) towards the interface normal are respectively θ_i , θ_r and θ_t .

Relations between these angles are set by the law of reflection and Snell's law. Fraction of intensity of the incident beam, reflected by the interface (in our case by the transparent roof), is presented as the coefficient of reflectance ρ_a . The refracted fraction is represented by the transmittance coefficient τ_a . Fresnel equations, based on the assumption that both materials are not magnetic, can be used to calculate the coefficients:

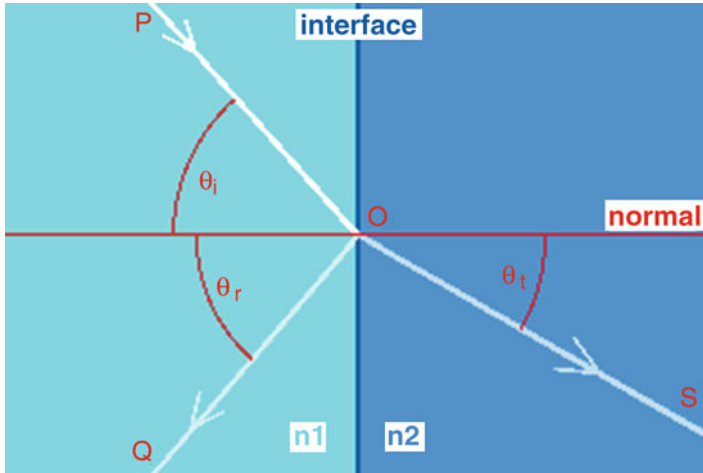


Fig. 3.35 Diagram of incident solar ray reflection and refraction

$$\rho_a = \left[\frac{\tan(\theta_t - \theta_i)}{\tan(\theta_t + \theta_i)} \right]^2 = \left[\frac{n_1 \cos(\theta_t) - n_2 \cos(\theta_i)}{n_1 \cos(\theta_t) + n_2 \cos(\theta_i)} \right]^2 \quad (3.51)$$

and

$$\tau_a = 1 - \rho_a. \quad (3.52)$$

According to Fresnel Eqs. 3.51 and 3.52 solar rays reflection can reach about 7.7% when the roof is made of glass. Also, an influence up to (15–20)% is exercised by the plant location. Solar towers located at a high latitude (Canada for instance) cannot produce more than 85% compared with a similar station located at the equator [33].

The following is an example of determining the basic parameters for a case study of a solar tower, which was to be built in a village in northern China, where solar radiation is more intense than in other regions. As a result of an analysis the site was chosen for the power plant construction, taking into account the location and solar radiation regime. A Solar tower with a diameter of 10 m, 200 m height and 500 m diameter of the collector is able to produce (110–190)kW of electricity per month the year round. Several parameters such as tower height, diameter of the solar collector, temperature of the environment, solar radiation and wind turbine efficiency, influencing energy generation performance, were also analyzed. Next, a list of all parameters considered for the solar tower design is presented:

- A_c plan area of solar tower, m²;
- A_{col} solar collector area, m²;
- C_p air specific heat, kJ/kg.°C;

g	<i>free fall acceleration, m/s²;</i>
G	<i>solar radiation, W/m²;</i>
H_{sc}	<i>solar tower height, m;</i>
$\dot{m}$	<i>air current mass per unit of time, kg/s;</i>
P_{tot}	<i>air flux total power, kW;</i>
$P_{wt,max}$	<i>maximum mechanical power generated by the turbine, kW;</i>
P_e	<i>electrical power generated by the solar tower, kW;</i>
$\dot{Q}$	<i>air received energy in the collector, kW;</i>
T_0	<i>environmental temperature, °C;</i>
V_c	<i>air velocity in the solar tower, m/s;</i>
$(\tau\alpha)-$	<i>derivative of transmittance and absorbance coefficients for the Earth's surface;</i>
β	<i>coefficient of losses, W/m².K;</i>
η_{col}	<i>solar collector efficiency;</i>
η_{sc}	<i>solar tower efficiency;</i>
η_{wt}	<i>turbine efficiency;</i>
ρ	<i>air density, kg/m³;</i>
ΔP_{tot}	<i>pressure difference between the lower and upper parts of the tower, Pa;</i>
ΔT	<i>temperature increase at output from collector, compared to input, °C</i>

3.3.3.3 Towers with Solar Collectors and Air Turbine: Practical Issues

Solar Energy Tower is a special power facility designed for renewable energy conversion. Air is heated in a large circular collector, and the resulting convection causes increased air speed when it passes through the tower. Moving, the air drives the turbine (or turbines), which produces electricity.

In the last 30–40 years a wide range of solar air collectors power plants have been invented. The operating principle of a solar air collector tower is described in the invention [34] presented in Fig. 3.36. It operates based on the principle of converting solar heat into electricity by means of accumulating unheated air in the air collector (1), which covers a large area of land. Heated air due to pressure difference circulates through a very tall tower (2) of large diameter, located in the centre of the roof. In the centre of the tower there is a support (3), on which an electric generator (4) driven by a turbine (or several turbines) (5) excited by the cold air passing through the tower, is mounted.

In order to increase the air velocity a pair of truncated cones is used, one of which (6), being mounted in a holder and passed by air currents, works as a convergent nozzle. The second truncated cone (7), installed at the outlet, works as a diffuser.

Generation capacity of a solar tower depends largely on two factors: the size of the collector and the tower height. The larger the area of the collector the greater amount of air is heated (collector diameter up to 7 km). At a big tower height (up to 1,000 m) the pressure difference leads to an increase of the furnace effect (Fig. 3.38).

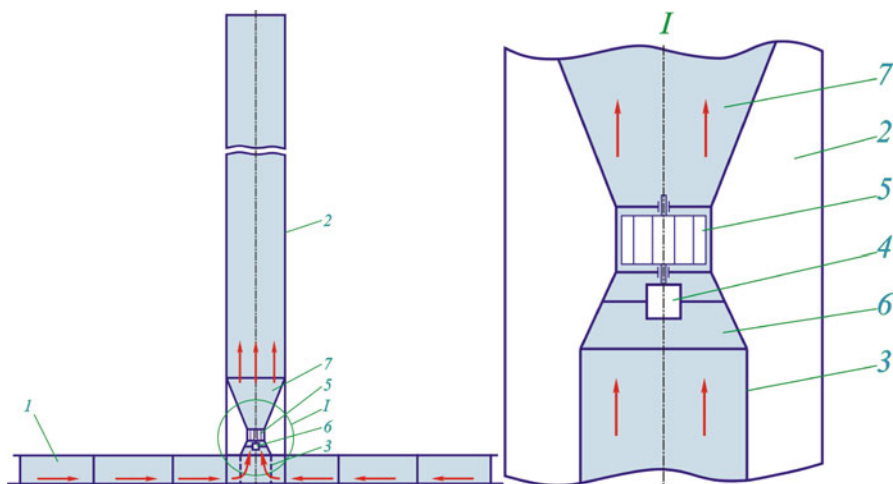


Fig. 3.36 The principle of converting solar heat into electricity by means of accumulating unheated air in the air collector

The combination of the effects of these two important parameters determines the energy facility productivity. Heat accumulated during the day may be partially stored in water pipes (reservoirs) placed on the collector's land area. The air velocity is approximately directly proportional to the increase of temperature difference (ΔT) in the collector and at tower's outlet. In multi-megawatt solar towers, the collector causes a 20°C temperature increase. This produces an increasing of air velocity up to 15 m/s. Solar towers do not produce carbon dioxide, but harmful materials are used in the construction, particularly cement. Payback period is 2–3 years [35, 36].

Turbines can be installed in a row at the basis of the horizontal axis tower (as in the Australian project) or a single vertical axis turbine can be installed inside the tower as in the prototype from Spain. Turbines in solar towers do not work due to air velocity only, but similarly to hydropower stations, static pressure is converted into rotary motion, using the turbine of the case study. Solar tower turbine, unlike wind turbine, operates in a closed air flow. Therefore the ratio of power to the rotor area is about 10 times higher than the same ratio of the wind turbine. Air velocity before the turbine and after it is about the same. The power generated is proportional to the product of volume currents per time unit and pressure differential on the turbine. To increase conversion efficiency, the propeller blades is adjusted during operation in order to regulate energy production by means of varying the speed of air and air currents. If the blades are parallel to air currents and allow air to flow freely through them, pressure on the blade is not created and electricity is not generated. Between these two extremes the optimal position of the blades is situated: generated power is the highest if the pressure drop on the turbine is about 80% from available pressure differential. Optimal fraction depends on the plant characteristics as pressure loss due to friction (Fig. 3.37).

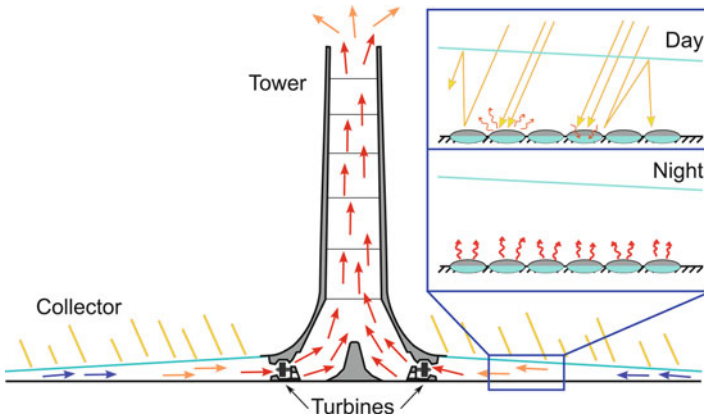


Fig. 3.37 Operation principle of the solar tower with circular collector



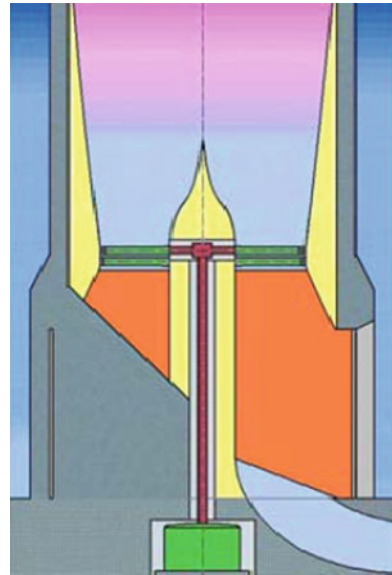
Fig. 3.38 Solar tower prototype's Manzanares, Spain, 1981

Detailed theoretical investigations and conducted extensive aerodynamic tunnel experiments [20] allowed in 1981–1982 the construction of an experimental 50 kW peak production facility in Manzanares district, Union Electrica Fenosa utility (Fig. 3.38) with funds from the German Ministry of Research and Technology (BMFT). Table 3.11 gives basic dimensions and technical parameters of the Manzanares prototype.

Table 3.11 Basic dimensions and technical parameters of Manzanares prototype

Tower height	194.6 m
Tower radius	5.08 m
Average collector radius	122.0 m
Average height of roof	1.85 m
Number of turbine blades	4
Turbine blades profile	FXW-151-A
Velocity ratio of blade at velocity of air conveying	1:10
Operation mode	Individual or grid connected
Increase of collector's air temperature	$\Delta T = 20\text{ K}$
Rated output	50 kW
Collector coated with plastic membrane	40,000 m ²
Collector coated with glass	6,000 m ²

Fig. 3.39 Operation principle of the air turbine



The operating principle of wind turbine is presented in Fig. 3.39. The turbine (Fig. 3.40) [20] is installed separately in the solar tower in a steel frame at a 9 m height above ground level. Initial 2.5 m/s vertical wind speed may reach up to 12 m/s during turbine operation.

The roof of solar tower collector is usually manufactured from a transparent material: glass (Fig. 3.41) or plastic membranes. The roof must not only be transparent, but also sufficiently durable and have a reasonable price. Plastic membrane costs are lower than those of glass. Figure 3.42 [20] presents measurements made on June 8, 1987 in Manzanares: air speed in the tower and a typical day power production. Figure 3.43 [20] presents a comparison between the measured and calculated energy,

Fig. 3.40 Air turbine of the power plant prototype



Fig. 3.41 Glass roof of the power unit prototype in Manzanares

produced at Manzanares facility. A disadvantage of solar air collector tower is large collector area and relatively low efficiency. Decrease of this disadvantage can be achieved by increasing the height of the tower.

An ambitious project is the prototype solar power plant to be built in Australia by Germany. Solar tower will have 1 km height (Fig. 3.44).

Another interesting project, which is under development stage, is Monohans Solar Tower project, U.S. (Fig. 3.45) [37]. Monohans Region is a national leader in oil production, and officials and residents from this region want to start this renewable energy project. A greenhouse made of transparent material with a diameter of

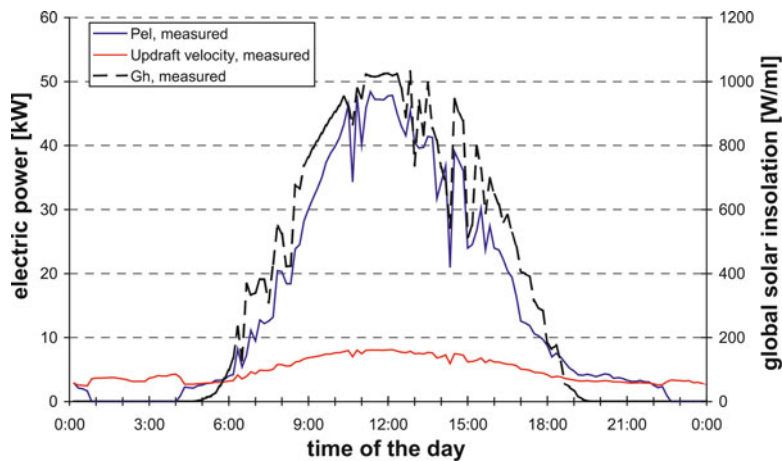


Fig. 3.42 Measurements made on June 8, 1987 in Manzanares: air speed in the tower and a typical day power production

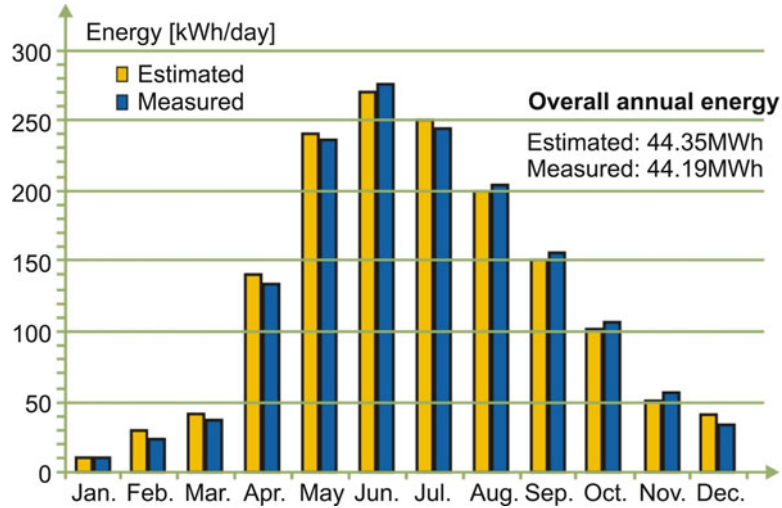


Fig. 3.43 Comparison of measured and estimated energy, produced by Manzanares power unit

2.5–3 miles shall collect warm air that will flow through 32 turbines located around the tower base. The difference in temperature between the turbine interior and the environment will ensure a steady air flow that will produce electricity. Solar tower will have a height of about 1,100 m and will produce 200 MW of green electricity, enough to supply approximately 200,000 houses. Project cost is estimated at approx. 350 million dollars.

To assess the energy potential of solar air collector tower, Table 3.12 [20] presents four typo dimensions of solar towers. Investment costs were calculated based on the data from Table 3.12. From Table 3.13 [20] it follows that the cost of

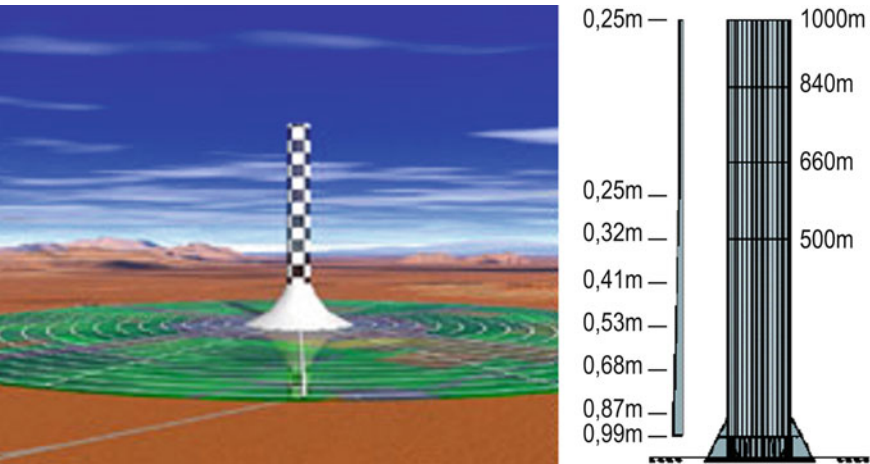


Fig. 3.44 Australian design of the solar electrical tower of 1 km height



Fig. 3.45 Design of the solar tower in Monohans, USA

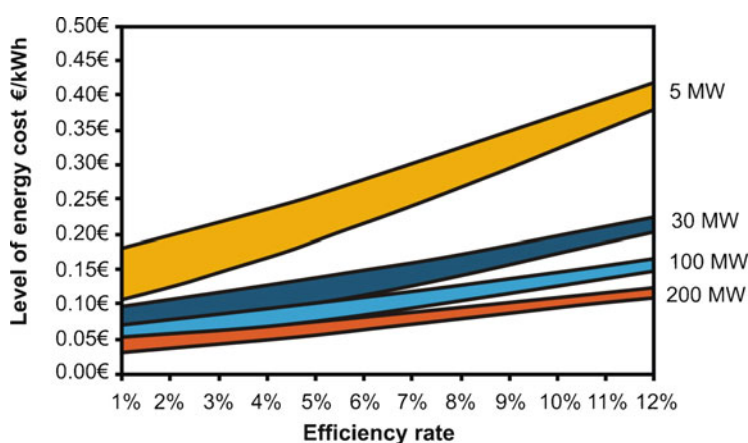
Table 3.12 Specific size and power capacity

Capacity	MW	5	30	100	200
Tower height	m	550	750	1,000	1,000
Tower diameter	m	45	75	110	120
Collector diameter	m	1,250	2,900	4,300	700
Electricity generation (production) ^a	GWh/a	14	99	320	680

^aFor locations with annual overall solar radiation 2,300 kWh/(m²year)

Table 3.13 Investment costs

Capacity	MW	5	30	100	200
Cost of tower ^a	Mln euro	19	49	156	170
Cost of collector	Mln euro	10	48	107	261
Cost of turbine ^b	Mln euro	8	32	75	133
Engineering, testing	Mln euro	5	16	40	42
Total	Mln euro	42	145	378	606
Annual instalment investments	Mln euro	2.7	10.2	27.1	43.7
Annual operation and maintenance costs	Mln euro	0.2	0.6	1.7	2.8

^aLabour cost – 5 euro/h^bBenefit rate – 6% and duration – 30 years**Fig. 3.46** Leveling cost of electricity depending on the selected efficiency ratio and on the solar tower

electricity for small solar towers is relatively high, compared to those of PV systems. Increasing the plant size is associated with significant decrease of generated energy cost reaching minimal cost values of 0.07 €/kWh for 200 MW plant.

Changes in the electricity costs depending on selected efficiency level, lifetime and installed capacity of solar tower, are presented in Fig. 3.46 [20]. The top line of graphs is calculated for 20 years lifetime, and the lower – for a lifetime of 40 years. As shown, the cost depends on the desired efficiency ratio and the lifetime (life time or depreciation period). For example, for a 12% efficiency rate and a 20-year depreciation, the cost for 200 MW solar tower is 0.12 €/kWh. For a 6% efficiency rate and a 40-year depreciation period, the cost decreases to 0.06 €/kWh, that is, in half.

Figure 3.49 considers a comparative analysis for the costs of electricity produced by coal-fired power plants and by a solar tower. In the first years of operation the cost of electricity generated by solar towers, is greater than that produced by coal-fired power plants. Costs are the same after 20 years of operation. Further, the solar

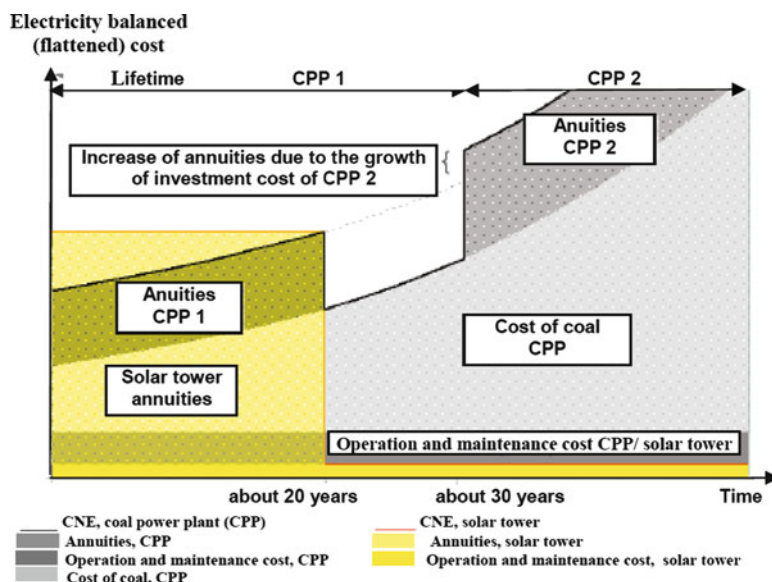


Fig. 3.47 Electricity generation cost for solar tower and coal thermal power plant

tower will generate electricity at low cost (including only operating and maintenance costs). In contrast, electricity generation costs of coal power plants are relatively high and imposed by the permanently growing cost of coal. This fact does not take into account the costs for environmental protection (meeting an approved CO₂ emissions level) for coal power plants.

In Moldova, where the Sun shines 2,200 h a year (in the south – 2,300 h/year) and annual amounts of radiation are about 1,350 kW/m² [38], there are favourable conditions for the development of such solar energy capture systems, which can be combined with plant cultivation technologies in green houses (Fig. 3.47) [20].

3.3.4 Solar Systems with Solar Rays' Concentration

3.3.4.1 Brief History

The power density of solar radiation on the Earth's surface rarely exceeds 1,000 W/m². Using plane collectors analysed above, it becomes impossible to obtain temperatures greatly exceeding 100°C. Temperatures of hundreds or even thousands degrees can be obtained only through the concentration of solar radiation direct component.

Legend says that in 212 BC Archimedes used for the first time the effect of Sunlight concentration. With polished-to-shine soldier shields (thus becoming

genuine bronze mirrors) Sunlight was reflected and concentrated in such a manner that allowed burning the Roman ships besieging the Syracuse fortress. In order to verify the legend, in 1973 the Greek Naval Authority showed how 60 people, each with a mirror sizing 1×1.5 m (1.5 m^2), burned a wooden ship situated at 50 m distance [4]. If during the experiment the radiation density was about 800 W/m^2 , than in the centre it was about $0.8 \times 1.5 \times 60 = 72 \text{ kW/m}^2$, thus exceeding 1.5 times the power density on the surface of an electric heating plate.

This way of capturing solar energy always is in the attention of researchers. L. Stoddard and others have conducted extensive studies on the economic, environmental and energy benefits of Sunlight concentrating systems [39, 40]. The largest group, which focuses on research and use of concentrated Sunlight solar systems, is U.S. Solar Energy Generating Systems (SEGS), which developed and built in the Mohave Desert from southern California paraboloidal systems with a total capacity of 354 MW. These systems functioned very well during 15–20 years. Today SEGS has a number of commercial projects under development or under construction, including a 64 MW paraboloidal system in Nevada and several 50 MW systems in Spain. Integrated systems are at various planning stages in Southern California, India, Egypt, Morocco, Mexico and Algeria. A paraboloidal system has recently been built for Arizona Public Service [41].

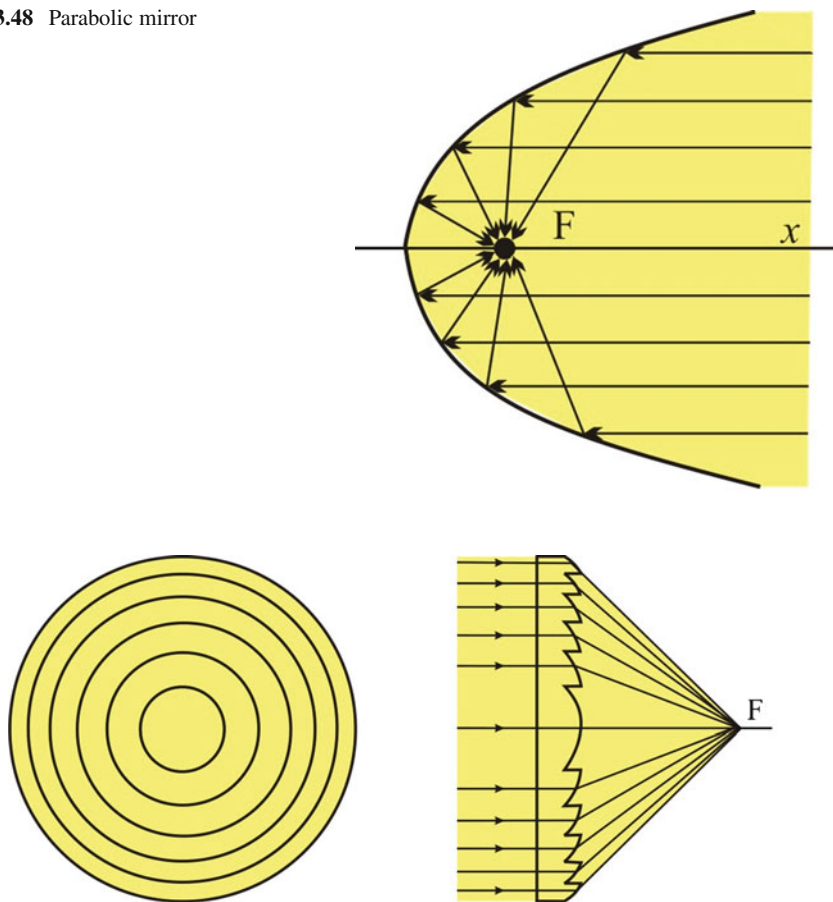
In 2005, Southern California Edison Company publicly announced the completion of contract negotiations with Stirling Engine Systems (SES) Company for the purchase of 1,182–2,010 GWh per year for a period of 20 years. As a result of large-scale development of these paraboloidal systems with Stirling engines significant reduction of capital and operating, as well as maintenance costs are expected [41]. Detailed information on Sunlight concentration solar systems can be found in [41, 42].

In general, three basic types of solar power plants with Sunlight concentration are known: cylindrical-parabolic systems (with gutters); with parabolic mirrors and Stirling engine; solar towers with heliostat concentrator.

3.3.4.2 Thermal Conversion of Solar Energy at High Temperatures: Theoretical Issues

Operation of solar concentrators is based on two phenomena studied by physics: reflection and refraction of light. If a surface is not rough or the linear sizes of a surface are much smaller than the wavelength of an incident light beam, this surface reflects. Surface reflection capacity is characterized by the reflectance factor. Reflectance values for common materials are:

– Galvanised silver	0.96;
– Pure aluminium	0.91;
– Silver deposited on the inner surface of the glass (mirror)	0.88;
– Silver deposited on the outer surface of the glass	0.93;
– Posterior surface aluminized acrylic film	0.85.

Fig. 3.48 Parabolic mirror**Fig. 3.49** Fresnel lens

Parabolic mirror. This is a concave mirror (Fig. 3.48), which surface is described by the parabola $y^2 = 2cx$ around the optical axis x . Figure obtained is called paraboloidal. A cylindrical-parabolic mirror is obtained if parabola is moved in the direction of z axis (axis perpendicular to the surface of the page). Rays of light parallel to the optical axis x , incident on reflective surface, concentrate in point F , called focus point

Fresnel lens: This is a unit composed of several concentric lenses (Fig. 3.49), which functions as an integral lens. Material and mass costs of a Fresnel lens are much smaller than those of a conventional one. Parallel light flux concentrates in focus point F .

The three types of solar energy concentrators used in thermal conversion are composed of three main components: the reflector that receives Sunlight and directs in to the focus point; the receiver, located in the focus point and that turns Sunlight

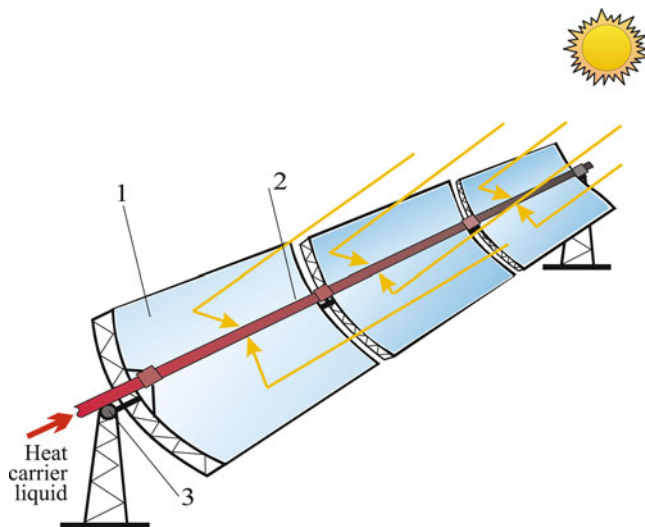


Fig. 3.50 Operating principle of cylindric-parabolic concentrator

into heat; Sun position tracking system. Fresnel-type concentrators are used in the photovoltaic technology of solar energy conversion only.

The basic parameters that characterize a solar concentrator are concentration coefficients. Geometric concentration coefficient is the ratio between surface area open to Sunlight, or aperture A_a , and receiver's surface area, A_r :

$$C_g = \frac{A_a}{A_r}. \quad (3.53)$$

Optical concentration coefficient is the ratio between the power density of direct radiation on the receiver's surface, B_r and power density of direct radiation on the aperture B_a :

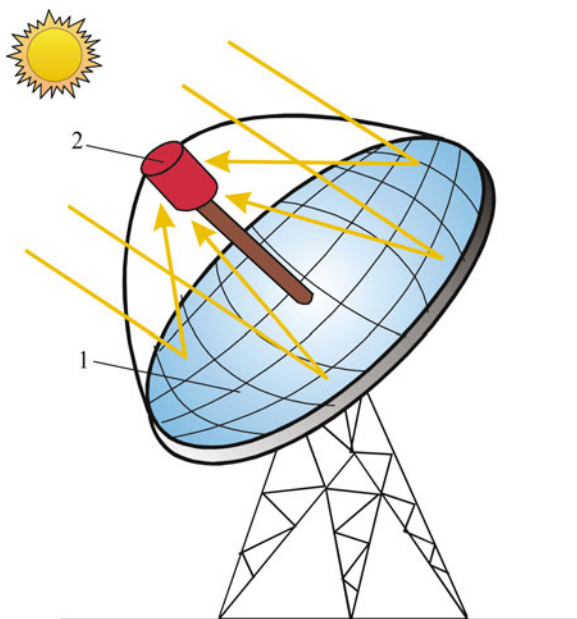
$$C_r = \frac{B_r}{B_a}. \quad (3.54)$$

For an ideal concentrator $C_g = C_r$, in fact $C_r < C_g$. Taking into consideration the distance between the Earth and the Sun disk diameter, the geometric concentration factor cannot be bigger than:

$$G_g < \left(\frac{2L}{D_s} \right)^2 = 45000. \quad (3.55)$$

Figure 3.50 shows a design diagram of the concentrator with three cylindrical-parabolic reflective mirrors (1) (in the form of a gutter). Solar radiation receiver (2)

Fig. 3.51 Operating principle of solar concentrator with paraboloidal mirror



represents a pipe through which the thermal agent fluid, usually water, circulates. The receiver (2) is mounted in the focus point of the parabolic cylinder, representing a line crossing the optical focus point F of the parabola from Fig. 3.48.

An important feature of the cylindrical-parabolic concentrator is the tracking of only one coordinate from Sun trajectory – elevation angle α_s (Fig. 3.49). In the construction from Fig. 3.50, tracking is done by rotating mirror 1 around the axis 3. Receiver temperature reaches 400–500°C.

The second concentrator type (Fig. 3.51) has a paraboloidal mirror (1) (in the form of a plate), serving as a reflector. The receiver (2) is mounted in the focus point of the paraboloidal. The orienting mechanism (not shown) must ensure tracking of two angles – elevation α_s and azimuth γ (Fig. 3.9). Receiver temperature can reach over a thousand degrees.

The heat collected is usually used directly by thermal engine mounted on the receiver, which moves with the plate unit. Concentrators of this type are used for melting and obtaining of most pure metals in ground conditions or for electricity generation. Stirling or Brayton heat engines are usually used as heat engines. Such modular systems with total capacity of up to 5 MWe have been manufactured. Maximal power registered for a module is about 50 kWe, achieving an efficiency of up to 30%.

The main advantages are:

- Rotation mechanism around two axes allows to collect the maximum Sunlight quantity;
- Easily transported and assembled modular construction;

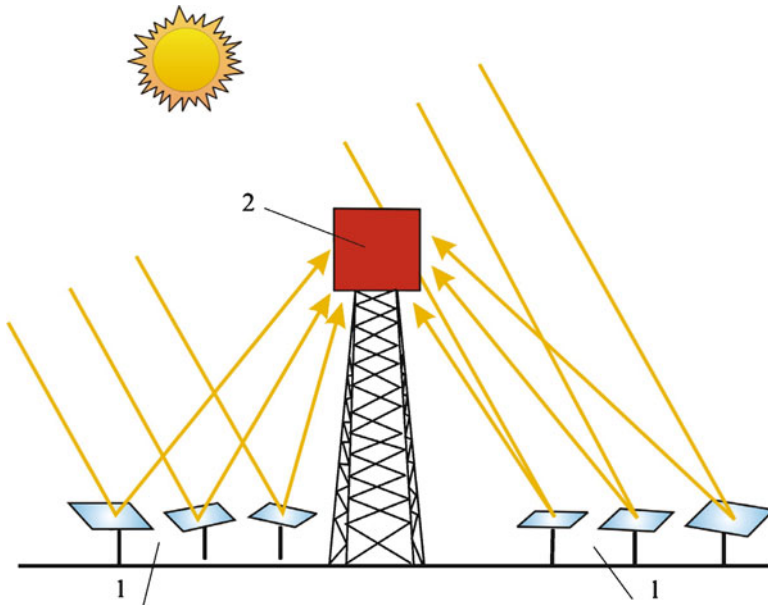


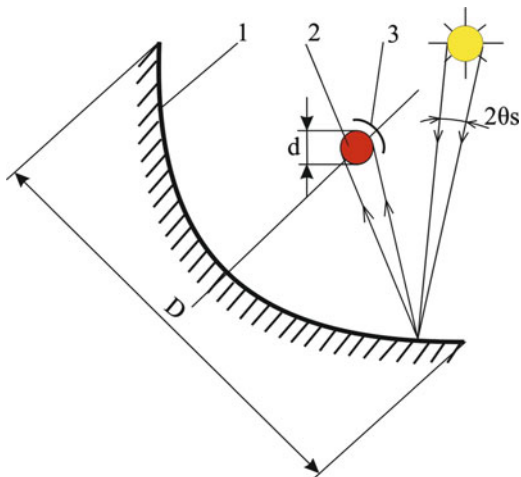
Fig. 3.52 Operating principle of the concentrator with heliostate

- Highest efficiency compared to any other generating solar technologies;
- Requires limited areas;
- Long operation period.

Heliostat concentrator is the equivalent of a very large parabolic concentrator (Fig. 3.52). Heliostats 1, small flat-shaped reflectors, are located around the entire circumference of the central tower forming the so-called heliostat field. The reflector 2 is mounted on the tower in the focus point of the paraboloidal. Each heliostat is remote-controlled and follows the two coordinates of the Sun position. The first heliostat concentrator was built in 1949 under the supervision of the French professor, Felix Trombe, in Mont-Luis area in the Pyrenees [43]. The heliostat field was situated on 130 m², receiver power reached 50 kW, and the temperature reached 3,000–4,000°C. The facility aimed the study and creation of new materials, in particular of composite materials.

To estimate the temperature of the receiver we use Fig. 3.53, which depicts a simplified diagram of parabolic mirror concentrator: 1 is a cylindrical-parabolic or paraboloidal mirror, 2 – receiver placed in the focus point of the parabola or of the paraboloidal, 3 – receiver screen. Cylinder-parabolic mirror has length l and opening D , and in the case of paraboloidal mirror – aperture diameter is equal to D . The receiver of cylinder-parabolic concentrator represents a pipe with diameter d and length l , or has a spherical shape with diameter d for paraboloidal concentrator. Solar disk angular size is equal to $2\theta_s$, where $\theta_s = r_s/L$ (Fig. 3.2).

Fig. 3.53 Simplified diagram of the parabolic concentrator



Temperature of the cylindrical-parabolic concentrator receiver: The power of solar radiation absorbed by the receiver:

$$P_{abs} = \rho_c \alpha l DB, \quad (3.56)$$

where ρ_c is the reflectance of mirror surface, α – absorption of receiver; B – direct solar radiation.

The receiver, having the temperature T_R , emits radiant power in space, which, according to Stefan-Boltzmann law, is determined by the expression (3.6):

$$P_{rad} = \varepsilon \sigma T_R^4 \pi d l (1 - \xi / \pi), \quad (3.57)$$

where ε is the receiver emissivity; σ – Stefan-Boltzmann's coefficient, ξ – shielding factor of receiver, usually $\xi = 2/3\pi$, d – diameter of the receiver, determined by the opening D : $d = D\theta_s$.

At steady heat condition absorbed power is equal to the radiated power (other power losses of the receiver are neglected), from where the maximum temperature of the receiver is determined:

$$T_R = \sqrt[4]{\frac{\rho_c \alpha B}{\varepsilon \sigma \theta_s}}. \quad (3.58)$$

For $B = 600 \text{ W/m}^2$, $\alpha/\varepsilon = 1$, $\rho_c = 0.8$, $\sigma = 5.67 \text{ W} \cdot \text{m}^2 \cdot \text{K}^{-4}$, $\theta_s = 0.00465 \text{ Rad}$, maximum temperature of $1,162^\circ\text{K}$ 889°C is obtained. In usual systems with cylindrical-parabolic concentrators temperatures up to 700°C are obtained. Temperature decrease is due to mirror surface deviation from the ideal parabolic shape and to the fact that liquid thermal agent circulating through the receiver, leads to P_{rad} decrease.

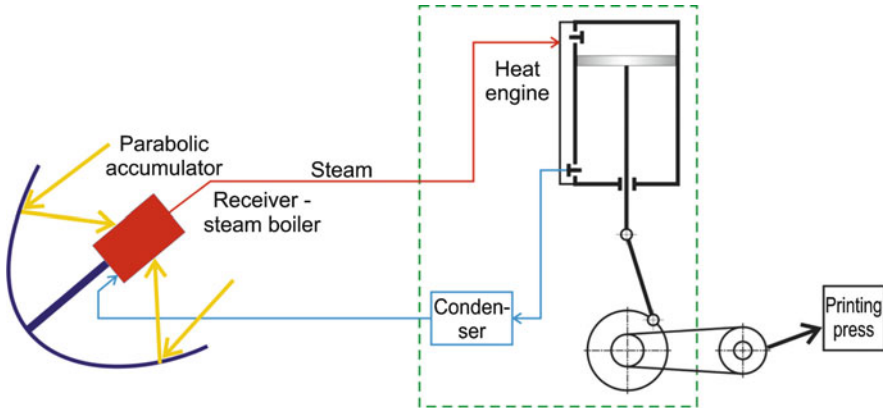


Fig. 3.54 Schema of solar thermal engine elaborated by Augustin Mouchot and Abel Pifre in 1872

Temperature of paraboloidal concentrator receiver. A sphere-shaped receiver with a diameter d is considered, other sizes and assumptions remain the same as in the previous case. From the thermal balance condition we obtain:

$$T_R = \sqrt[4]{\frac{3\rho_c \alpha B}{8\varepsilon \sigma \theta_s^2}}. \quad (3.59)$$

For the same amount of direct solar radiation $T_R = 3,480^\circ\text{K}$ or $3,208^\circ\text{C}$ are obtained. In real plants temperatures up to $3,000^\circ\text{C}$ can be obtained.

3.3.4.3 Heat Engines Used at Solar Thermal Plants

Solar thermal system with steam engine: working principle: Conversion of solar thermal energy into mechanical energy or electricity was the goal of experiments for over a century. At 1872 Paris exhibition professor of mathematics Augustin Mouchot and engineer Abel Pifre presented the first system converting solar energy into mechanical energy – a printing press driven by a steam engine powered by a solar parabolic concentrator (Fig. 3.54).

Later, in 1913, American entrepreneur Frank Shuman applies the same principle in Egypt, manufacturing the first solar unit for irrigation [43, 44]. The steam for the thermal engine was generated by five cylinder-parabolic collectors with an 80 m length and 4 m aperture each. The receiver – a cast iron pipe situated in the focus point, provided transportation of the steam to the engine. The unit developed a mechanical power of about 45 kW, which was used to pump water from river Nile for irrigation. Due to the high price of coal in that area at that time, system recovery period did not exceed 4 years.

It is necessary to note one very important disadvantage of solar heat engines – low efficiency. It follows from the low power density of solar radiation and the fundamental principles of thermodynamics. A more understandable interpretation of the second law of thermodynamics states: thermal or heat energy cannot be fully converted into other forms of energy, such as mechanical or electrical. The efficiency of a piston- or turbine heat engine depends on the warm source temperature, i.e. input temperature T_{in} and cold source temperature (condenser) T_{ies} , between which heat exchange occurs. Maximum efficiency or maximum Carnot efficiency can not exceed the value obtained from the expression:

$$\eta_C = 1 - \frac{T_{ies}}{T_{in}} \quad (3.60)$$

For example, a turbine powered by a steam parabolic concentrator at a 350°C temperature and a 30°C condenser temperature shall have a theoretical efficiency equal to $1 - (30 + 273)/(350 + 273) = 0.51$ or 51%. Real efficiency, due to energy losses shall be much lower than about 25%.

To obtain water vapours a temperature of at least 100°C is required. If temperature obtained from the solar collector is lower, than a heat engine employing Rankine cycle can be used. Here, as fluid thermal agent, organic substances are used that boil at below 100°C and used in refrigerators and heat pumps. Such a heat engine shall have an even lower efficiency. For example, a heat engine efficiency operating on 85°C vapours, obtained from a plate solar collector, and at 30°C condensing temperature shall not exceed 15%.

Solar thermal system with steam turbine: World War I caused the widespread use of internal combustion engines operating on petrol or diesel. Cheap oil era began and solar thermal systems have been forgotten for a period for over 50 years. They returned after the start of the 1973 oil crisis. A group of U.S. engineers led by G. Alexander performed in 1979 a new solar irrigation project in the Gila Bend area [4].

Figure 3.55 shows the operation scheme of this system. Primary energy is obtained from a 537 m² cylindrical-parabolic solar collector, which heats water to a temperature of 150°C at about 7 atm pressure. The hot water circulates through the heat exchanger, working as a boiler too, pre-heater and receiver. In the secondary circuit (not shown in the diagram) of the heat exchanger, the working fluid Refrigerant 113 with a low boiling temperature is used. The vapours with 138°C temperature and about 9 atm pressure are used to power a turbine which drives the pump. Part of vapours is used to preheat the water in the primary circuit. After the turbine vapours are used in the regenerator to heat the water from the preheater circuit. The regenerator vapours condense in the condenser, where part of the water pumped is used for cooling and at a temperature of about 32°C is returned to the tank. In the first year of operation, the system worked for 323 h at a capacity between 240 and 570 l/s or 364 and 2,052 m³/h. In the second year it worked for 188 h, delivering 1.24×10^5 m³ [4] or at a capacity of 660 m³/h.

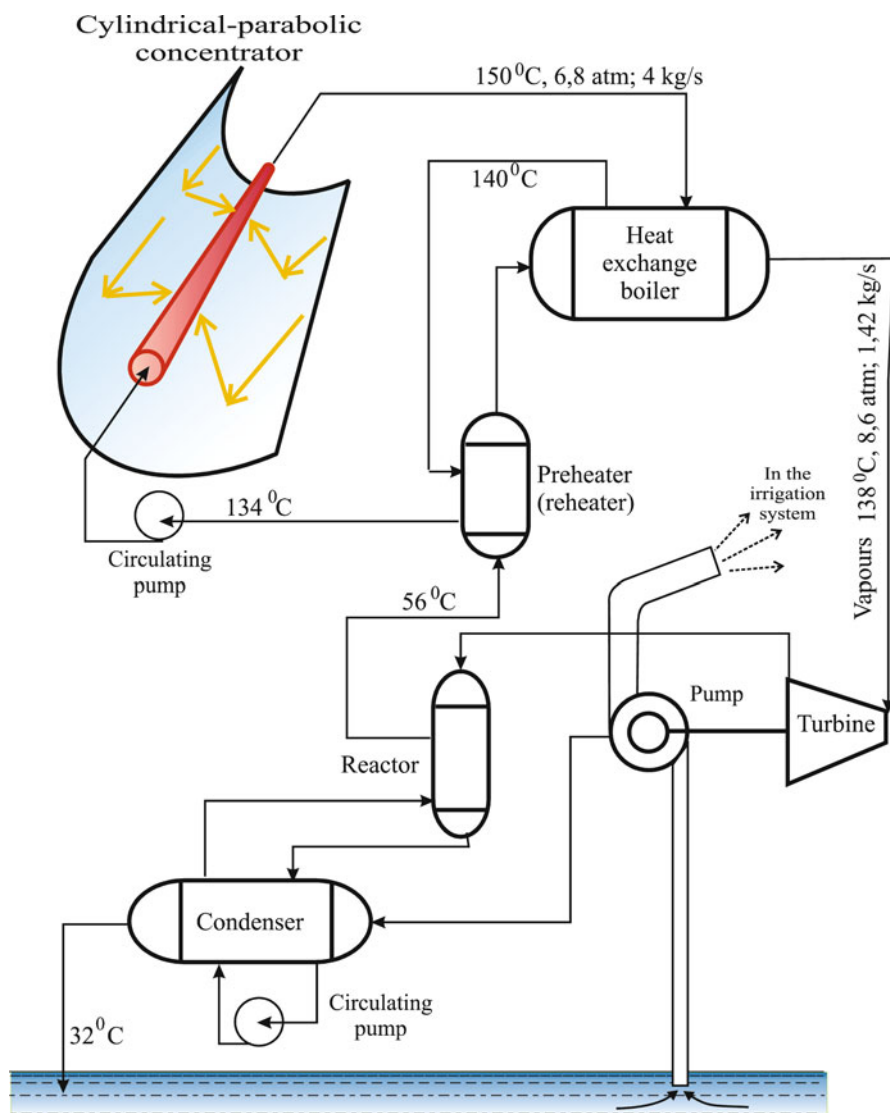


Fig. 3.55 Solar pumping system, manufactured by G. Alexander in 1979

Stirling engine solar thermal systems. For more than 20 years Stirling engine parabolic solar technology is in the focus of researchers. Figure 3.56 shows structural drawing of a paraboloidal concentrator solar thermal system (plate) and Stirling engine. The system includes a parabolic concentrator (plate) (1), heat receiver (2) and a heat engine/heat generator (3), which are installed on a support 4 with a concentrator orientation mechanism towards the Sun 5 (Fig. 3.56). Stirling engine is used as heat motor/generator.

Fig. 3.56 Operating principle of the solar unit with Stirling engine

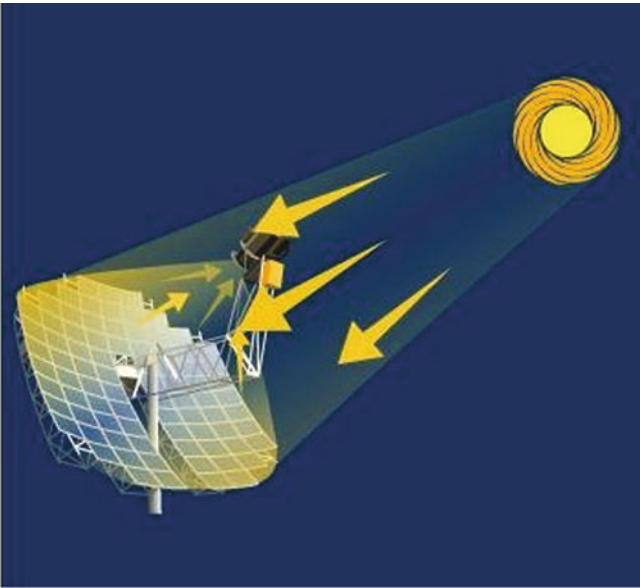
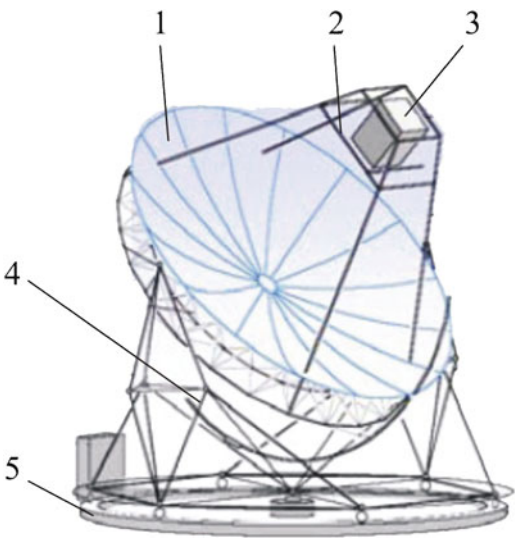


Fig. 3.57 Solar rays concentration principle in the Stirling engine unit

The operation principle of Stirling engine parabolic solar system and of Stirling engine is shown in Fig. 3.57. Parabolic concentrator reflects solar radiation received by the cavity of the receiver, located in the focus point of the concentrator. Generated temperature heats Stirling engine working agent and makes it operational. To better

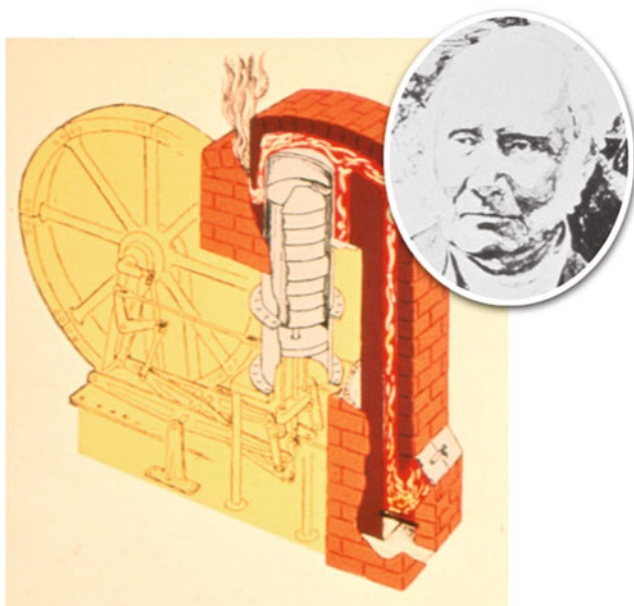


Fig. 3.58 The first Stirling engine

understand the issue, a brief history, construction and operating principle of the Stirling engine is presented.

On 27 September 1816 Robert Stirling patented his Economizer in Edinburgh, United Kingdom (Fig. 3.58). At that time Robert Stirling was a minister in the Church of Scotland, where he continued to work until the age of 80. During this time, he built his heat engine at home. Lord Kelvin used one of his models for demonstrations at the university. Simple and elegant dynamics of the engine has been explained for the first time in 1850 by Professor A. McQuorne Rankine. Approximately 100 years later the term *Stirling engine* was used by Rolf Meijer to describe all types of closed-cycle regenerative engine.

This engine is a unique heat engine because its theoretical efficiency is almost equal to the maximal theoretical efficiency, known as the Carnot efficiency. Stirling engine (Fig. 3.59) is driven by the expansion of the heated gas, followed by its compression when cooled. Stirling engine contains a fixed quantity of gas which is transferred back through the hot and cold areas. The distribution piston moves the gas between both ends of the cylinder and the power piston changes the internal volume of gas through compression and expansion. The gas used in the Stirling engine does not leave the engine during operation. Unlike petrol and diesel engines, Stirling engine contains no valves, no explosion occurs. Stirling cycle uses an external source of heat, which can be anything – from gasoline to solar energy. No combustion takes place in the Stirling engine. Solar radiation is absorbed by a heat exchanger (receiver) and it heats the working gas (helium or hydrogen) of

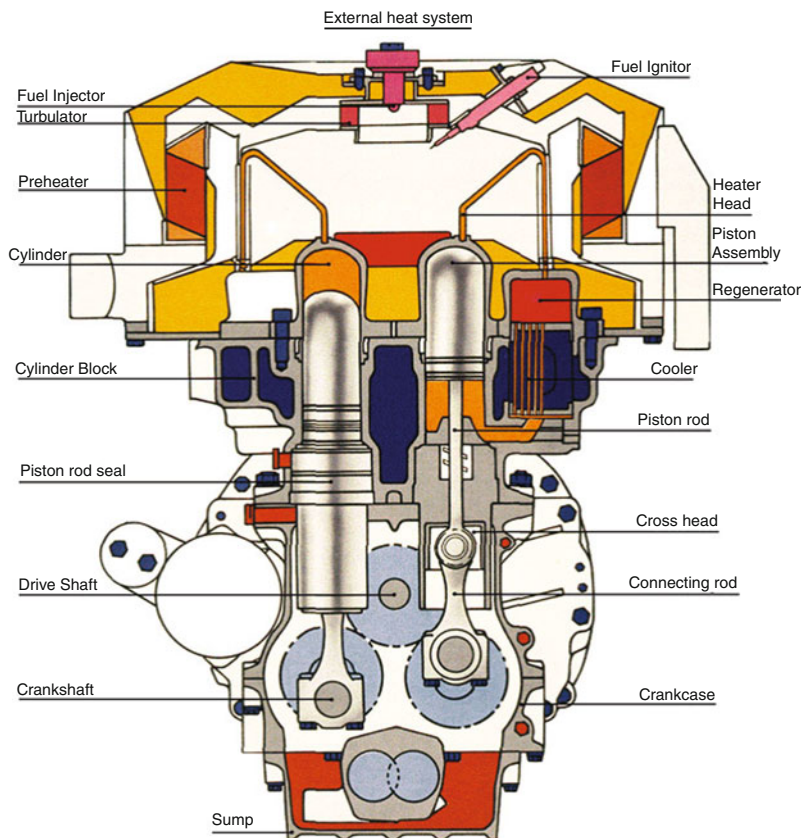


Fig. 3.59 Operating principle of Stirling motor

the Stirling engine up to temperature of about 650°C (Fig. 3.60). Stirling engine converts this heat into mechanical energy.

Stirling engine shaft turns mechanical energy into electricity. Theoretically possible efficiency of the Stirling heat engine is about 60%, compared with 45% for the diesel engine and no more than 30% for standard Otto engine. Parabolic modules with Stirling engine can produce between 5 and 40 kW. A network of modules can be used for producing electricity in large quantities.

3.3.4.4 Solar Thermal Power Plants (STPP) with Cylindrical-Parabolic Concentrators

The conversion of solar thermal energy into electricity is similar to the traditional conversion, based on fossil fuels where energy stored in the fuel is released through combustion, and is converted into potential energy of compressed and heated to

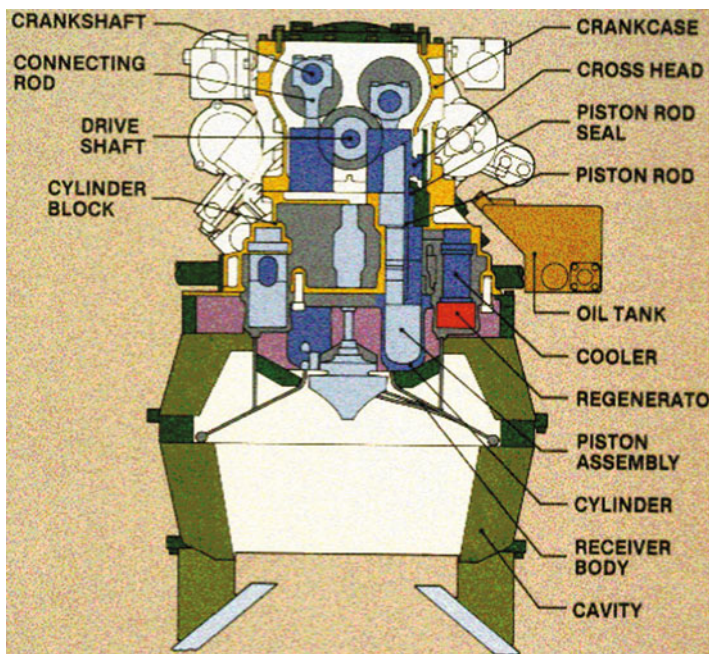


Fig. 3.60 Heat receiver embedded in Stirling motor

500–600°C steam. In the turbine, the steam expands, the potential energy turns into kinetic energy which, in its turn, transforms into electricity. In solar systems, fossil fuel is replaced by solar radiation, boiler combustion chamber – with a concentration solar collector: cylindrical-parabolic, with parabolic mirror or with heliostat and central tower. Solar thermal collectors with focused Sunlight are mainly used to generate electricity. There are various systems that differ in the way how they collect and concentrate solar rays, but the final step of generating electricity is identical to that of conventional power plants. Finally, the heat engine is used to convert heat into electricity. The solar system is designed to focus solar rays and transform them into heat, which is used in the heat engine. In a simple way, solar thermal plant is a conventional power unit that uses solar energy as primary source of heat.

In the last two decades of the previous century in the U.S. several STPP pilot projects have been successfully completed, which proved their technical and technological viability and paved the way towards new projects with hundreds of MW capacity. Next, a brief description of certain commercial projects with cylindrical-parabolic concentrators is given [4, 44]. The largest solar thermal plant in the world has a maximum power of 354 MW and is located in the Kramer Junction area, California, USA [45]. It was built by Luz International Company in 1985–1991 and consists of nine units with an electric capacity between 14 and 30 MW. Later this type of plant was called LUZ solar system. Figure 3.61 shows a part of

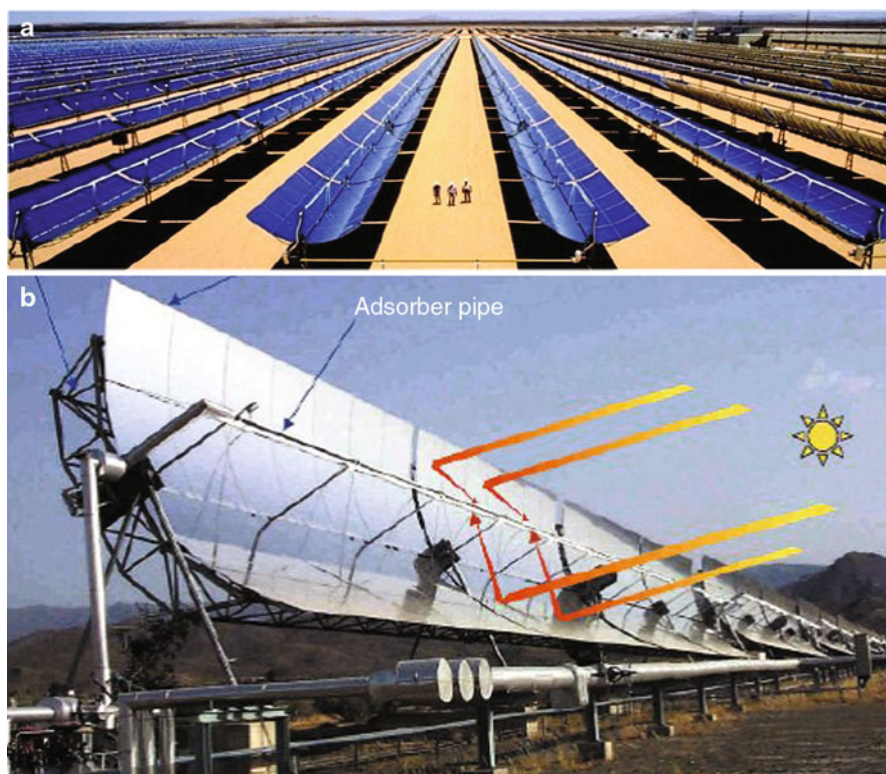


Fig. 3.61 Fragment of field with cylindric-parabolic solar collectors of the thermal power plant Kramer Junction (a) and a separate line (b), California [46]

cylindrical-parabolic concentrators' field. By 2001 the facility supplied in the public network of California 9 TWh of electricity. The plant is equipped with an auxiliary circuit, operating on natural gas and allowing expansion of energy production by 25% either on cloudy weather or during peak hours. The plant was designed to provide electricity during peak hours, when the cost of delivery is the highest. In California this period lasts from June to September, 12:00–18:00 h. Main plant components are shown in Fig. 3.62. Solar collector field is composed of cylindrical-parabolic concentrators with a total area of about $1.75 \times 10^6 \text{ m}^2$. The active part of the concentrator – the reflector is composed of low-iron glass and coated with silver at the back. Glass is mounted on a metal sectioned frame, which allows the formation of different length collectors. The collectors are mounted in parallel rows in the south–north direction. The Sun is tracked using hydraulic drives. The solar radiation receiver has a 70 mm steel tube in diameter covered with a layer of selected material (see Sect. 3.3.2.4). To reduce energy losses, the receiver is placed in a vacuum glass tube. At a temperature of 350°C , the surface receptor has an absorbance equal to 0.96 and an emittance of 0.19 only.

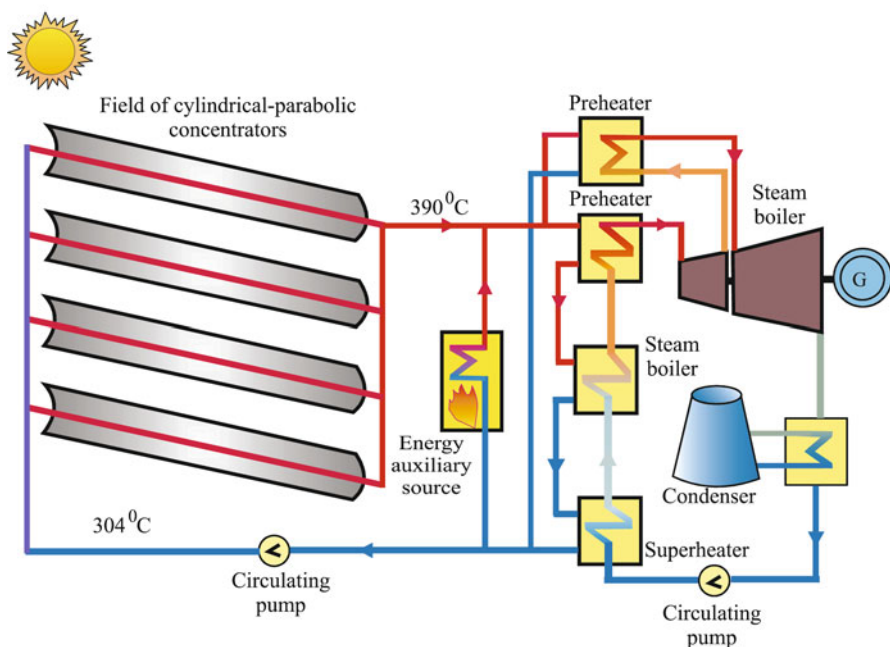


Fig. 3.62 Operating diagram of solar thermal plant from Kramer Junction, California

Reflectance of clean mirrors is equal to 0.94. In the first contour, which includes solar collectors, a synthetic fluid (usually oil) is used as thermal agent. The fluid leaving the collector has a temperature of 390°C , and at the entrance of the collector – about 304°C . In the second circuit water turns to steam into the boiler supplied with thermal energy from solar collectors. The generating unit represents a traditional group ‘steam turbine-synchronous generator’. Steam turbine has two pressure stages – the first is supplied with superheated steam and the second – from the preheater.

Solar Energy Generating Systems (SEGS) owns the largest collection of parabolic systems in the world. Nine facilities are located in the Mohave Desert in Southern California. SEGS plants were built during 1985–1991. A large network of 80 MW SEGS plants is located in the Harper Lake area. All SEGS plants are hybrid, using fossil fuel to supplement solar power during periods of low solar radiation. Each plant is allowed to generate 25% of annual energy using fossil fuels. The hybrid SEGS plants capacity factor exceeds 100% in peak-hours for more than a decade, with more than 85% of electricity obtained from solar energy. In general, SEGS plants operate well. New models of heat collector elements increase the plant performance and reduce costs.

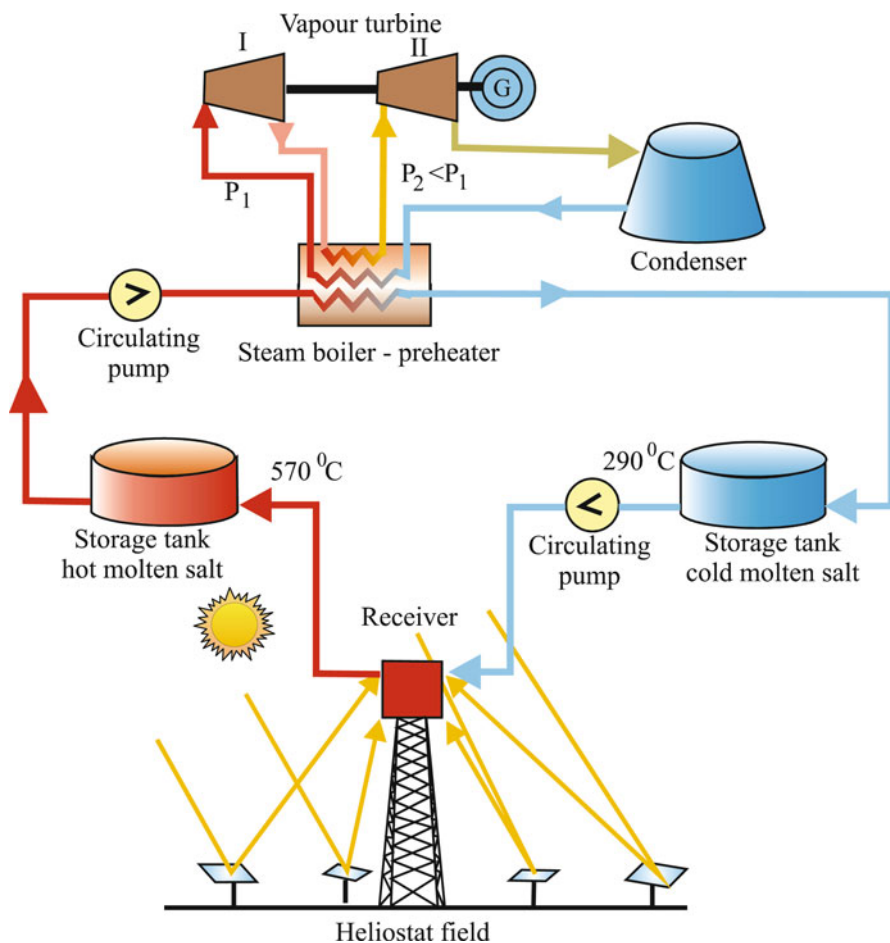


Fig. 3.63 Operation principle of solar thermal plant Solar Two

3.3.4.5 Solar Thermal Power Plants with Heliostats and Central Tower

Solar thermal power plants with heliostats and central tower (or, in short, solar towers) use thousands of mirrors called heliostats, which redirect concentrated solar light to the receiver that is installed at the top of the tower. With most receivers, salt solution heated in the receiver is used to generate steam directly into the receiver, steam that is used by a conventional turbine generator to produce electricity. Molten nitrate salt possesses heat transfer properties and has superior energy storage capacity. Commercial power towers can be sized to produce from 50 to 200 MW electricity. In international practice, systems with air as working fluid in the receiver are used. Figure 3.63 shows the technological scheme of high temperature solar receiver solar tower. In the 90s of the last century several pilot



Fig. 3.64 Solar thermal plant Solar Two [48]

plants with heliostats and central tower were built: in the former USSR – employing 5 MW power; in Italy, Spain and France – employing 1 MW power.

The world's largest heliostat plant was built in 1982 in the U.S., Barstow district, California. The plant was called Solar One and has a 10 MW capacity [4, 45, 47, 48]. The operating principle of the heliostat solar concentrator is described in Sect. 3.3.3.2. A general view of the plant is shown in Fig. 3.64. After 6 years of operation, in 1988 it was decided to rebuild the plant. It was equipped with a thermal energy storage system with molten salt; heliostats control system has also been modernized. Heliostat field includes 1818 reflectors with a total area of $71,100 \text{ m}^2$.

Each heliostat is oriented so as to reflect Sunlight on to the receiver installed in the centre of the field at 90 m above the ground. A heliostat includes 12 concave panels with a total area of 39.12 m^2 . Glass coated with silver was used as reflecting material. The receiver is a 13.7 m height- and 7 m diameter cylinder. The receiver cylinder consists of 24 panels, each having a 0.9 m width and 13.7 m height.

An interesting European project, similar to the above, is 3,000 SOLAIR system installed in Almeira region, Spain. Concentrated solar rays are reflected on an open volumetric absorber part of the receiver. Environmental air heated to $680\text{--}750^\circ\text{C}$ supplies the steam generator to produce electricity. This system has a 70% rate of converting solar energy to heat at a temperature of up to 700°C . A high efficiency is obtained at a temperature of $590\text{--}630^\circ\text{C}$ and at incident solar light of



Fig. 3.65 Stirling paraboloidal system (SES)

310–370 kW/m². Being the most efficient system to date, an inherent disadvantage of it is the complexity of the scheme (high maintenance costs) and heat loss in multiple heat exchange processes.

3.3.4.6 Paraboloidal Solar Thermal Power Plants with Stirling Engine

Stirling engine parabolic solar technologies have been demonstrated in a variety of complete systems over the past two decades and can move further towards commercial application over the next 5 years. Several U.S. and European projects are aiming at the use of solar energy this way. Stirling engine paraboloidal units have several common characteristics compared to the wind turbines. Like wind turbines, Stirling solar parabolic units are an intermittent energy source, include a base that can be built within a few days, are small power energy facilities and are modular units. Regarding Stirling parabolic units marketing, some wind turbines market penetration tactics may be used.

Figure 3.65 presents a Stirling paraboloidal system including an air heating system and a mechanism for rotating the parabolic mirror concentrator around two

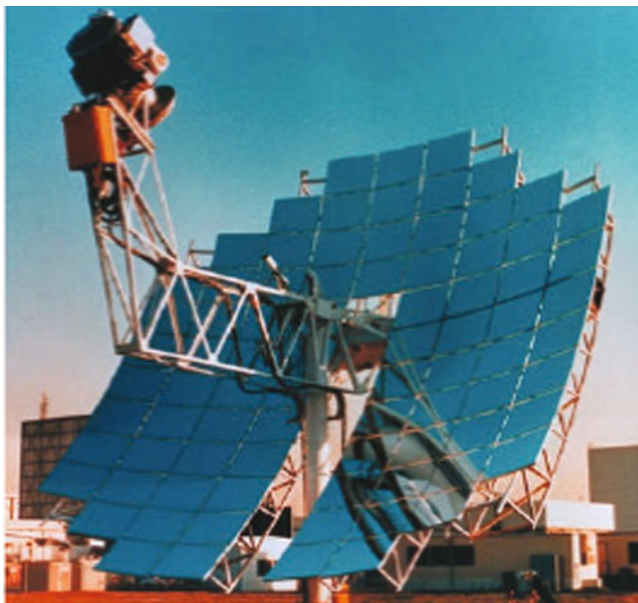


Fig. 3.66 Stirling paraboloidal system with working agent – hydrogen

axes. This allows the collector to be continuously oriented to the Sun. The system was designed and built by SES (Stirling Energy Systems), which together with the STM Company today are most aggressive in implementing Stirling parabolic systems on the market. They are engaged in developing and building new Stirling parabolic facilities. In SES opinion, engine and collecting system changes will increase peak efficiency of the coming plants by 10%. This is a new efficiency world record for any solar electricity generation technology and it will increase the annual electricity production by 6.3%. Stirling parabolic system (Fig. 3.66) uses an efficient Stirling engine. Solar energy is converted into heat in a closed hydrogen spiral. Heated hydrogen drives Stirling engine-generator.

Due to air cooling it does not require water cooling as in the solar cylinder-parabolic systems or solar towers. Thermal energy storage is not considered a viable option for Stirling parabolic systems. Relatively flat land is preferable to build and maintain these systems. At the same time, land requirements are less important than for cylindrical-parabolic solar systems or solar towers. An individual Stirling parabolic plant produces 10–25 kW. Having high efficiency and modular construction, the cost of these systems is expected to be competitive on the market. According to the estimates of SES, the main developer of Stirling parabolic systems, costs of parabolic concentrators shall dramatically decrease hundreds of times at larger power stations (MW level) or at network connection. Stirling parabolic facilities are not yet marketed, being in the experimental stage. Recently at Sandia National Laboratories (SNL) in Albuquerque (USA) an installation with six parabolic mirrors has been tested. In August 2005, Southern California Edison



Fig. 3.67 *Stirling engine – electrical generator unit of paraboloid power plant*

Company publicly announced the completion of negotiations with SES for the right to use Stirling parabolic facilities of 500–850 MW capacity (annual production between 1,182 and 2,010 GWh/year) over a 20-year period. In September 2005, SES publicly announced a contract with San Diego Gas & Electric to develop solar plants with capacities between 300 and 900 MW.

Purchase price for these rights remains confident information. Development of large scale Stirling parabolic systems will cause drastic reduction of capital and operation and maintenance costs, and will result in increased system reliability. Figure 3.67 shows the “Stirling engine-electric generator” node. Figure 3.68 shows a field with Stirling engine parabolic solar systems located in California, USA.

Further, Figs. 3.69a, b and 3.70a, b present a Stirling parabolic system, developed and patented by the authors [49, 50]. The examined solutions propose to simplify the transformation mechanism of the alternative movement of Stirling engine pistons into rotary motion. Crank mechanism and the cams (see the original construction of the Stirling engine above) of a Stirling engine is replaced with a precessional planetary transmission 2, which reduces the speed of output shaft 3 of Stirling engine. Precessional transmission satellite block 4 is connected kinematically with piston rods 5 of the Stirling engine, which allows direct conversion (without using additional elements) of alternative translational motion of the pistons into reduced rotation of electric generator.

In order to spin paraboloidal concentrator together with Stirling engine in an azimuth and zenith plane precessional drive mechanisms 6 and 7 (Fig. 3.69a, b) are used. These, due to very high transmission ratio (up to 3,600 at single stage) ensure



Fig. 3.68 Field of Stirling (SES) paraboloidal solar systems, California

very slow rotational motions (basically, a rotation around the axis of the tower for 24 h) required for permanent orientation of Stirling paraboloidal system after Sun position. Precessional drive mechanisms developed are compact and reliable, containing a small number of elements compared to other transmission systems, and this provides low cost.

3.3.5 Photovoltaic Systems

3.3.5.1 Brief History of Photovoltaic Technologies

The term “*photovoltaic*” is derived from the combination of the Greek word “*photos*” – meaning *light*, and the name of the electromotive force unit – *volt*. Thus, photovoltaic technology (PV) describes the generation of electricity using light. In 1839, during the industrial revolution, Alexander Edmond Becquerel, the father of Nobel laureate Henri Becquerel, discovered the photovoltaic effect, which explains how electricity can be generated from sunlight. He concluded that “*illumination of an electrode immersed in a conductive solution would create an electric current*” [51].

Despite extensive research, after this discovery, photovoltaic conversion continues to be ineffective. Photovoltaic cells were used mainly for measuring of light intensity proposals. The first report on photovoltaic or photoelectric effect, as it was

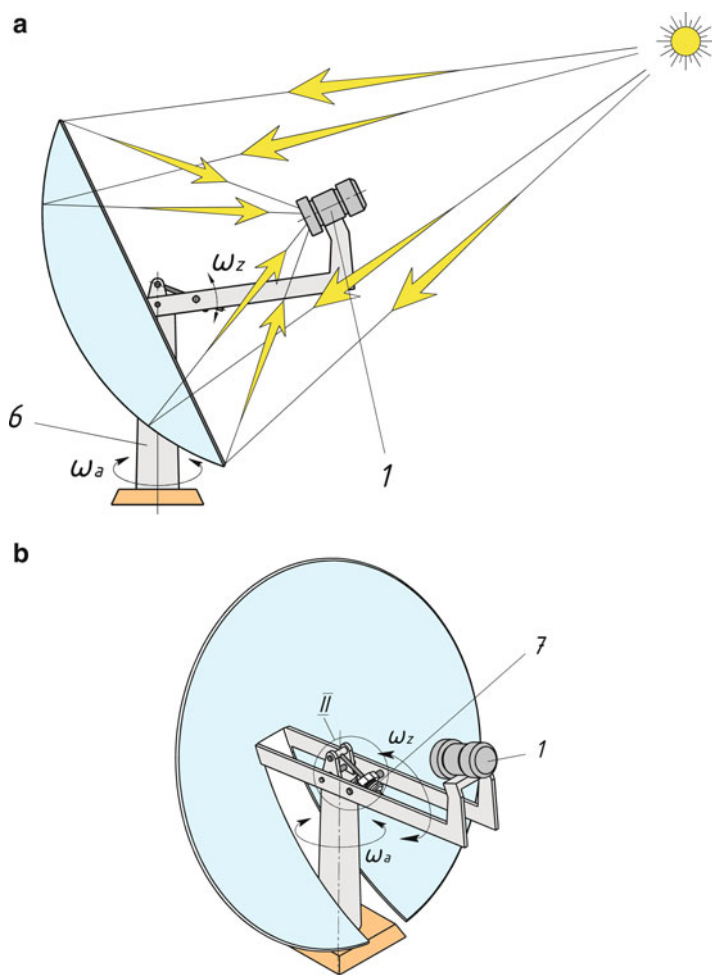


Fig. 3.69 Stirling paraboloidal solar system, author's elaboration [49]

called at that time, was done by Cambridge scientists W. Adams and R. Day in 1877. The report described changes that occurred in light-exposed selenium plate. In his experience, Heinrich Hertz noticed in 1887 that a zinc plate is loaded with positive charge when exposed to ultraviolet radiation. The phenomenon is due to the same photoelectric effect: the action of ultraviolet rays separates electrons from metal, as a result the metal is positively charged.

The first PV cell was built by an American electrician, Charles Fritts, in 1883 using selenium. Construction of the cell was patented in 1884. It should be noted that the construction of the cell was very similar to today's cells. However, cell efficiency was less than 1% and the industrial use has not been realized.

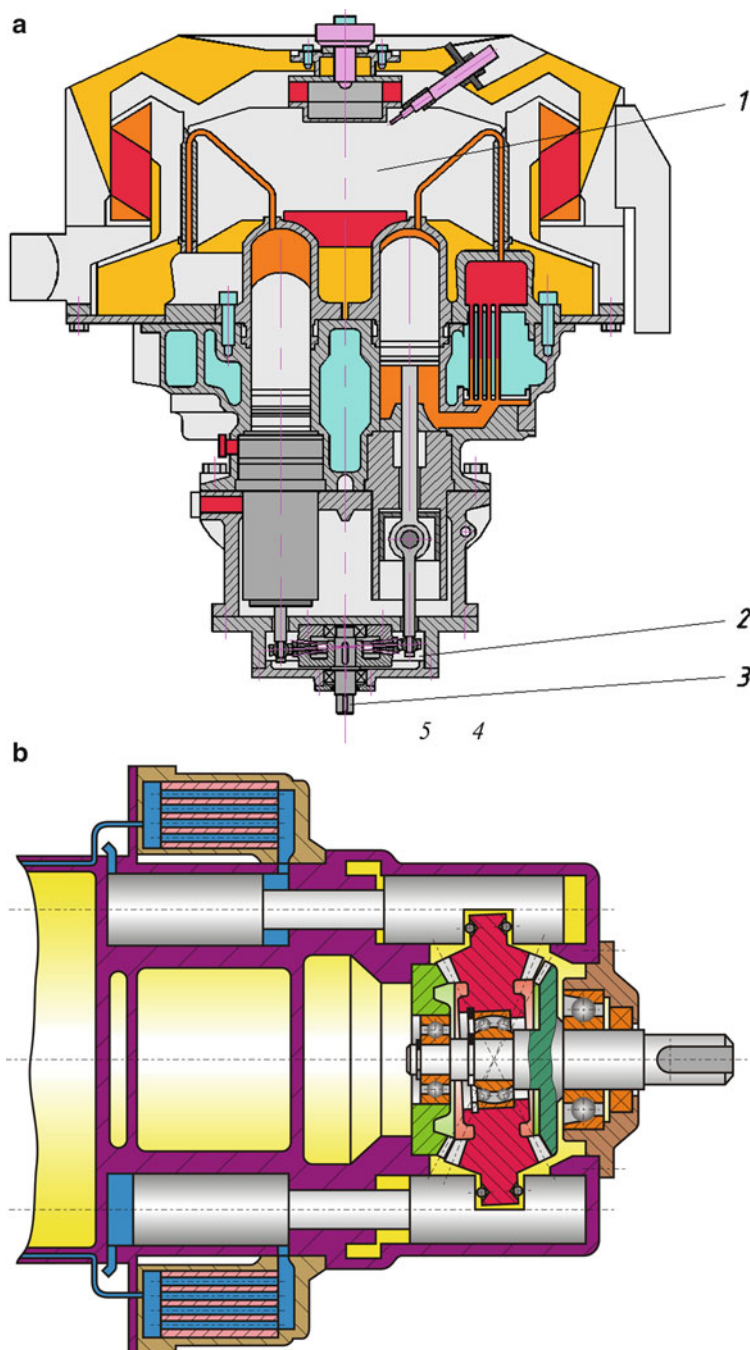


Fig. 3.70 Stirling engine with piston rods linked kinematically to precessional transmission satellite, author's elaboration [50]

After about a century since the first discovery of the effect, Albert Einstein in 1921 received the Nobel Prize in physics for explaining the photoelectric effect that allowed the practical use of photovoltaic cells. In 1946, Russell Ohl invented the solar cell [52], followed by the invention of the transistor in 1947.

In the middle of twentieth century scientists and engineers returned to the study of the photovoltaic effect, occurring in semiconductors. In 1953, a Telephone Laboratories (Bell Labs) team of engineers, D. Chapin, C. Fuller and G. Pearson, creates the silicon PV cell with a much higher efficiency than the selenium cell. The following year, the same team built a silicon cell with a 6% efficiency. At the same time, first consumers of photovoltaic energy – artificial satellites, have appeared. In 1957, PV cells were installed on the first artificial satellite of the earth “*Sputnik 3*”, and in 1958 PV cells were installed aboard the U.S. satellite Vanguard 1 and served to power a radio transmitter. Until these days PV cells are the most suitable energy sources for space machinery. Competition between the USA and the former USSR in the 60s of last century in the field of sources for electricity supply of the satellites led to a spectacular development of PV technology and caused a breach in the rigid dependence of decentralized energetics from traditional sources: electrogen units, storage batteries or dry cell batteries. A new competition started – to bring PV generator back to earth. Governments of industrialized countries and many private companies have invested billions of dollars in the development of PV technology.

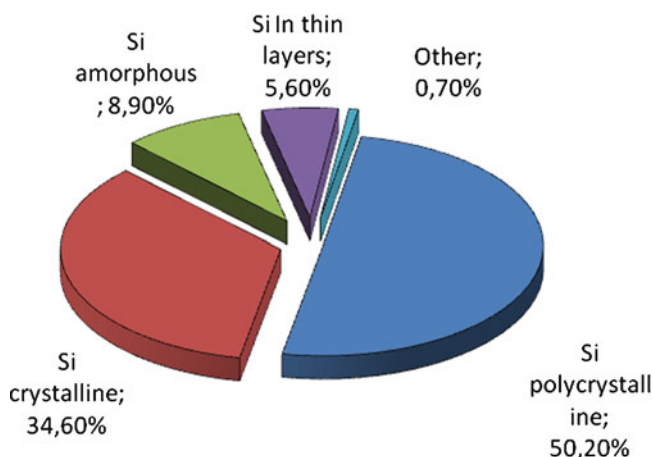
By using the photovoltaic effect direct conversion of sunlight into electricity occurs. Direct conversion technology excludes intermediate transformations: solar radiation to heat, heat to mechanical energy, and mechanical energy into AC power. Direct conversion is performed using semiconductor materials and the photovoltaic effect. Photovoltaic generator, the so-called photovoltaic cell, unlike the electromechanical generator produces DC electricity. Elimination of intermediate processing from the technological chain, lack of motion, noise and vibration, modular construction, a service life of over 25 years, are arguments in asserting that the future of decentralized energy shall belong to photovoltaic technology. Not accidentally, on 31 August 1991 The Economist magazine mentioned the following about the photovoltaic solar energy conversion: “*Of all alternative energy sources – wind, sea wave, tidal, geothermal – perhaps the most promising solar energy conversion into electricity is photovoltaic one*”.

3.3.5.2 Photovoltaic Cell: Characteristics and Technical Parameters

Construction and operating principle: Photovoltaic cell is an optoelectronic device which operation is due to the generation of light by free charge carriers and their separation by the internal electric field of p-n, MOS or Schottky junctions. Crystalline or polycrystalline silicon is used as initial material for manufacturing in which, usually, by various technological methods different conductive layers are formed to obtain p-n junction. Basic semiconductor material used to produce PV cells is silicon. Table 3.14 shows the PV conversion efficiency based on three types of photovoltaic materials: crystalline silicon, polycrystalline silicon and amorphous silicon [53, 54].

Table 3.14 Materials comparison for PV cells

Solar cell material	Crystalline silicon	Polycrystalline silicon	Amorphous silicon
Power conversion efficiency (%)	15–22	14–15	7–10

**Fig. 3.71** World market distribution depending on the materials for PV cell production

Global market share of different technologies for producing PV cells is shown in Fig. 3.71. Over 84% of world production of PV cells is based on polycrystalline and crystalline silicon. Today, polycrystalline and crystalline silicon technology is the most advanced, ensures the production of PV modules on an industrial scale with a yield of 14–17% and a 30 years lifetime of modules.

But this technology has a crucial disadvantage – limited potential for future decrease of PV cell production costs. Experts in the field believe that the cost of a watt will not drop below 2 euros [55–57]. From this point of view, technology of amorphous silicon and silicon in thin layers is a promising perspective. The costs of 1 W produced with these technologies will decrease to 1 € – the limit cost for PV electrical energy is cheaper than electrical energy produced from fossil sources. It is assumed that for these reasons in recent years there has been a redistribution of the global market in favour of amorphous silicon and in thin layers technology.

Figure 3.72 shows a schematic diagram of the simplified design of PV cell, based on *p*-type semiconductor material. Consider the phenomena that occur when PV cell is exposed to incident radiation (Fig. 3.72). This radiation can be equalized with a flux of photons, which have energy $E = h\nu$, where h is Planck's constant and ν is photon frequency. If the photon energy is bigger than the energy of the semiconductor power forbidden band, then, from the photon interaction with an atom, the electron from the valence-bond band will pass into the conduction band, becoming free, and generating also in a gap in the valence-bond band. Thus,

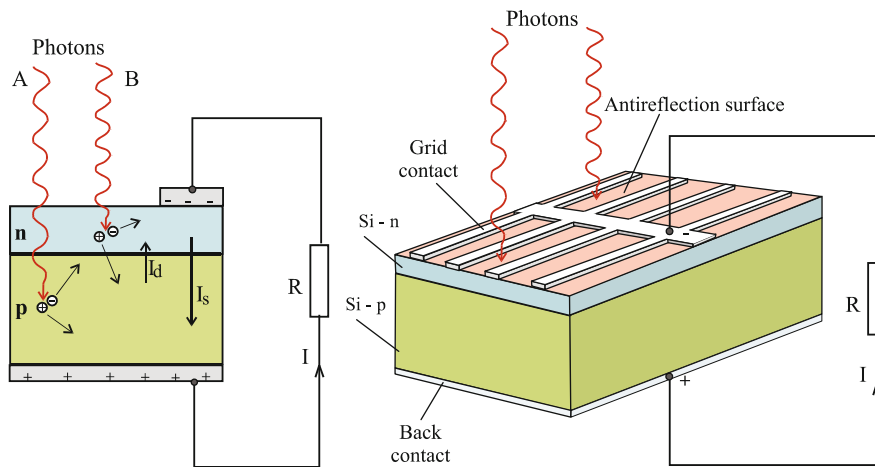


Fig. 3.72 Design diagram of photovoltaic cell

under the action of photons, generation of hole–electron pairs occurs. This is called internal photovoltaic effect.

In Fig. 3.72 on the left, the photon A has a lower frequency and therefore a lower energy, and photon B has a higher frequency and, correspondingly, a higher energy (low-frequency electromagnetic wave penetrates to large depths of the material and vice versa). Free charge carriers are separated from the electric field of the p - n junction, characterized by the barrier potential U_0 and which, depending on the type of semiconductor used, is about 0.2–0.7 V.

Here, the electric field will serve as free load break switch – hole–electron pairs. The electrons will be directed to the n zones, the holes – to the cell p zone. This is why, under the influence of light, p zone is positively charged and zone n – negatively charged, which leads to an electric current through the external circuit, caused by photovoltaic conversion of solar radiation. This current (Fig. 3.72 on the left), leads to a voltage drop U in the external load R connected to the rear contacts and to the front-grid contact (Fig. 3.72 on the right). Voltage U compared to p - n junction acts against the direct sense and, in its turn, will determine via the junction the diode I_d current against the inverse direction of photovoltaic current I_s which is determined from the known expression:

$$I_d = I_0 \left[\exp \left(\frac{eU}{kT} \right) - 1 \right] \quad (3.61)$$

where: I_0 is the saturation current strength; k – is Boltzmann's constant; T – absolute temperature; e – is the electron charge.

Photovoltaic cell characteristics: The main characteristics of PV cells are as follows: ampere-volt $I(U)$ or volt-ampere $U(I)$ characteristic and power characteristic

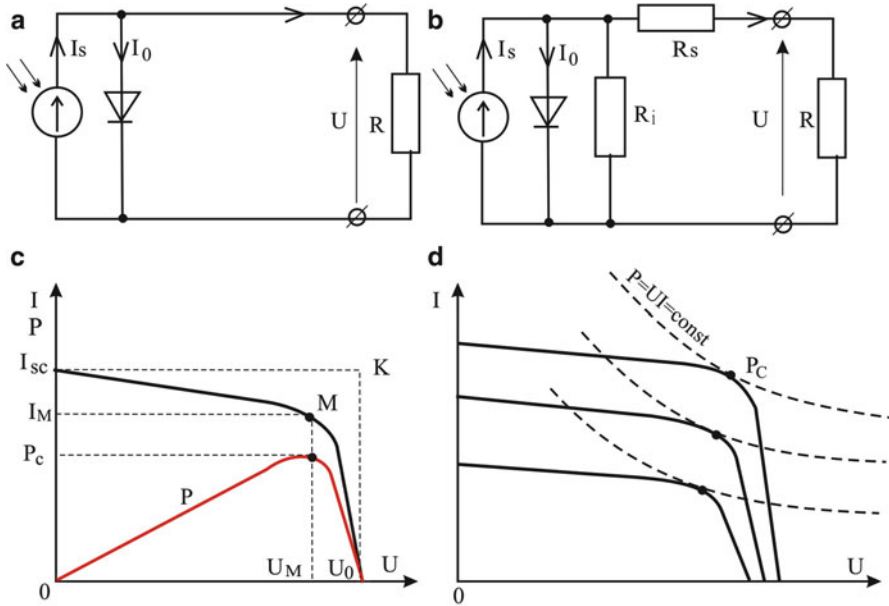


Fig. 3.73 Equivalent diagrams of PV cell: (a) simplified; (b) complete; (c, d) cell characteristics

$P(U)$. The current in the external circuit I is determined by the difference between photovoltaic current I_s and the diode current I_d [2, 57–59]:

$$I = I_s - I_d = I_s - I_o \left[\exp \left(\frac{eU}{kT} \right) - 1 \right] \quad (3.62)$$

The simplified equivalent circuit of PV cell, shown in Fig. 3.73a, corresponds to Eq. 3.62. If we take into account the leak resistance R_i of the PV cell p - n junction and the cell base-spreading resistance R_s , a complete equivalent scheme of PV cell can be produced (Fig. 3.73b). Modern technologies help to obtain cells with $R_i = \infty$ and $R_s = 0$, so that the simplified equivalent circuit is satisfactory.

Electrical power transferred to load R of a PV cell is:

$$P = UI = U \left\{ I_s - I_o \left[\exp \left(\frac{eU}{kT} \right) - 1 \right] \right\}. \quad (3.63)$$

Maximum value of power is obtained at point M of the current–voltage characteristic, which coordinates are derived from the condition $dP/dU = 0$:

$$\begin{aligned} U_M &= U_0 - U_T \ln \left(1 + \frac{U_M}{U_T} \right), \\ I_M &= I_s \left(1 + \frac{I_0}{I_s} \right) \frac{U_M}{U_M + U_T}, \end{aligned} \quad (3.64)$$

where $U_T = kT/e$.

For a passive load, the optimum value of load resistance is:

$$R_M = \frac{U_M}{I_M}. \quad (3.65)$$

Parameters PV cells and modules: Manufacturers of PV cells and modules show in the technical book of the product the technical parameters for standard conditions:

- Global solar radiation on the cell surface, $G = 1,000 \text{ W/m}^2$;
- Cell temperature, $T_C = 25^\circ\text{C}$;
- Conventional air mass, $AM = 1.5$.

It is compulsory that the book lists the following information: short circuit current, I_{sc} , no-load voltage, U_0 , maximum or critical power, P_C , voltage and current in the critical point, U_M and I_M . Besides these parameters, additional indicators may be: the Fill Factor, FF , efficiency of PV cell or module, normal operating temperature of the NOCT cell, coefficients of variation of no-load voltage and short circuit current with the temperature.

Short circuit current: It occurs at shorting of load R terminals as shown in Fig. 3.73. On the I - U characteristic this is the point with coordinates $U = 0$, $I = I_{sc}$. From the expression (3.62) for $U = 0$, we obtain $I_{sc} = I_s$. The engine power is zero.

No-load voltage: Corresponds to the point on I - U characteristic with coordinates $I = 0$, $U = U_0$. The rated power in this point is equal to zero. No-load voltage can be determined from Eq. 3.62 for $I = 0$:

$$U_0 = \frac{kT}{e} \ln \frac{I_s + I_0}{I_0} \approx \frac{kT}{e} \ln \frac{I_s}{I_0}. \quad (3.66)$$

For silicon cell the ratio I_s/I_0 is about 10^{10} , factor kT/e , called thermal voltage, is equal to 26 mV. Thus, $U_0 = 0.6 \text{ V}$.

Critical or maximum power: It is the product of current and voltage in point M of I - V characteristic. This parameter is called the *peak power* and is noted by P_C .

$$P_C = U_M \cdot I_M. \quad (3.67)$$

Geometrically, critical power P_C meets the tangent points of hyperbolas $P = UI = \text{const.}$ for the ampere – volt I - U characteristics (see Fig. 3.73).

Fill Factor is determined as the report between the surfaces of rectangles OU_MMI_M and OU_0KI_{sc} (Fig. 3.73c) or

$$FF = \frac{U_M I_M}{U_0 I_{sc}}, \quad (3.68)$$

Where

$$P_C = FF \cdot U_0 \cdot I_{sc}. \quad (3.69)$$

Fill factor is the measure of the PV cell quality. The lower internal resistance R_s of PV cell the bigger FF . Usually $FF > 0.7$.

Efficiency of PV cell or module: is determined with the ratio between the generated power of the PV cell or module in the optimum operating point M for a specified temperature and the solar radiation power

$$\eta = \frac{P_C}{A \cdot G}, \quad (3.70)$$

where P_C is the delivered power in W; A is the surface of cell or module in m²; G – global radiation incident on the cell or module surface in W/m².

A PV module with an efficiency of 12% and with the surface area of 1 m², exposed to solar radiation equal to 1,000 W/m² will produce approximately 120 W.

In laboratory conditions crystalline silicon cells have been obtained with an efficiency of 13–25% depending on the cell surface, and in factory conditions – 12% to 14%. Polycrystalline silicon cell efficiency is up to 20% in laboratory conditions. Theoretical limit of the crystalline silicon cell efficiency is 37% and that of amorphous silicon – 28% [60].

Normal operating temperature of the cell: corresponds to the temperature of PV cell in no-load operation conditions at the environment temperature of 20°C, global radiation of 800 W/m² and wind speed smaller than 1 m/s. For usual cells NOCT parameter is between 42°C and 46°C. If NOCT parameter is known, it is possible to determine the cell temperature T_C for other operating conditions characterized by the environment temperature T_A and global radiation G [59]:

$$T_C = T_A + \left(\frac{NOCT - 20}{0,8} \right) \cdot G. \quad (3.71)$$

The influence of solar radiation and temperature on the characteristics of PV cells and modules: PV cell characteristic for different solar radiation values are presented in Fig. 3.74a.

It is noted that the short circuit current is directly proportional to solar radiation and no-load voltage is varying a little, since according to Eq. 3.66, voltage U_0 depends logarithmically on solar radiation (I_s is proportional to the radiation) and often in practical calculations this variation is neglected. Short-circuit current, for different values of solar radiation G , can be determined with a satisfactory approximation of the formula:

$$I_{sc} = \frac{G}{G_{st}} \cdot I_{scst}, \quad (3.72)$$

where I_{scst} is the cell short circuit current corresponding to the standard radiation $G_{st} = 1,000$ W/m². PV cell temperature significantly influences the no-load voltage and less – short-circuit current (see Fig. 3.74b). With increasing temperature, no-load voltage decreases. For silicon cells the voltage variation coefficient of

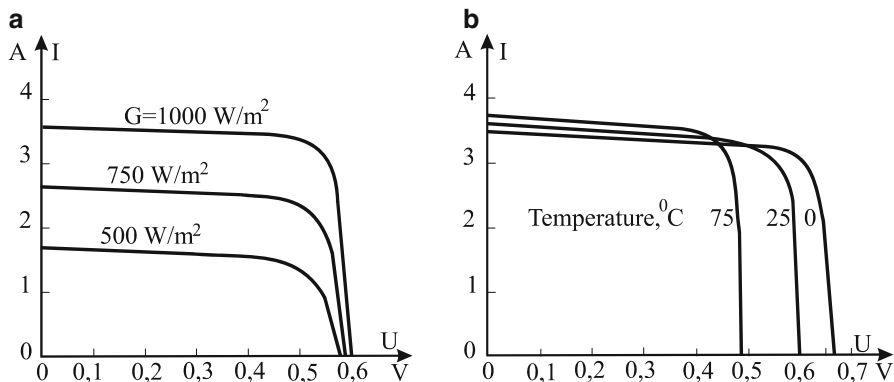


Fig. 3.74 PV cell characteristics at variation of solar radiation (a) and temperature (b)

temperature K_T is equal to $2.3 \text{ mV}/^\circ\text{C}$. Thus, the parameter U_0 for the temperature different from the standard is calculated by following equation:

$$U_0 = U_{025} - 0.0023(t - 25) \quad (3.73)$$

where U_{025} is the PV cell short circuit current corresponding to the standard temperature; t – current temperature of the cell, $^\circ\text{C}$. In the design calculations variation of short circuit current and of the filling factor FF depending on the temperature is neglected.

3.3.5.3 Photovoltaic Modules

Modern photovoltaic cells produce electrical energy which does not exceed $1.5\text{--}2 \text{ W}$ power at voltages from 0.5 to 0.6 V . To obtain voltage and power necessary for the consumer, PV cells are connected in series and/or parallel. The smallest photoelectric installation, consisting of PV cells connected in series and/or parallel and encapsulated to obtain greater strength and protect cells from environmental action, is called photovoltaic module. A number of PV modules assembled mechanically as one larger unit and electrically connected is called panel or field of modules. In accordance with the standards of the International Electrotechnical Commission (IEC) the term “array” is used, which means system or network. The terms “photovoltaic module”, “photovoltaic panel” or “field of modules” very often have the same meaning. When designing PV modules take into account the frequent use of PV modules for charging electric batteries, whose voltage is $12\text{--}12.5 \text{ V}$. Thus, in standard radiation conditions, voltage U_M must be $16\text{--}18 \text{ V}$, and no-load voltage – $20\text{--}22.5 \text{ V}$. A single cell generates in open circuit approximately 0.6 V and it is necessary to connect $33\text{--}36$ cells in series to obtain the necessary voltage. The module power will vary between 50 and 100 W . PV module construction (Fig. 3.75a) is usually rectangular.

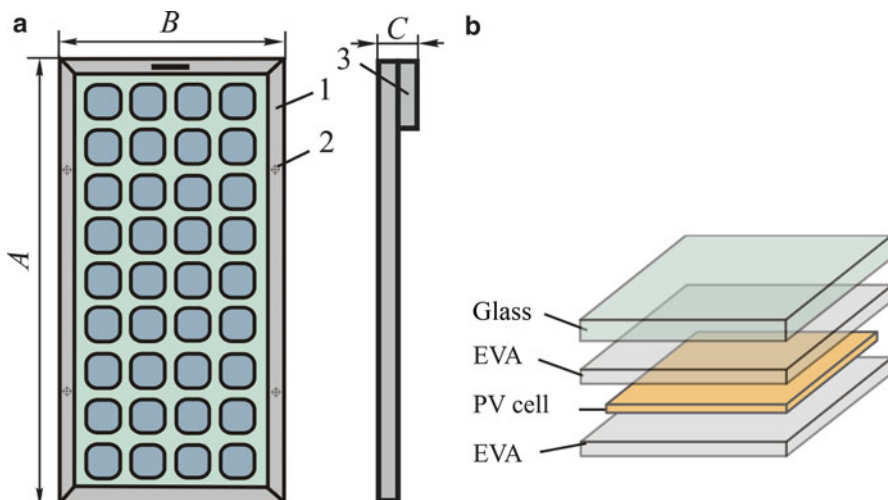


Fig. 3.75 Design of PV module (a) and PV cell package (b): 1 – support; 2 – panel assembly holes; 3 – terminal box

The support is made of anodized aluminium rod and separated from the cell laminated structure by lining that prevents moisture intrusion. PV cells are protected from unfavourable conditions impact that may occur during operation: rain, hail, snow, dust, etc., by a system which consists of a layer of glass and at least two layers (front and rear) of ethylene vinyl acetate EVA or PVB polyvinyl butyral (Fig. 3.75b). Figure 3.76 shows PV modules of various powers, manufactured by Kyocera Company, and in Table 3.15 – their basic characteristics. To obtain the necessary voltage and power for the consumer of electrical energy, PV modules can be connected in series, parallel or in series-parallel (see Fig. 3.77a, b, c). At series connection of two identical PV modules the current delivered to the consumer remains the same, and voltage increases twice. In Fig. 3.79, PV1 and PV2 modules connected in series charge GB storage battery. Operating point of the system “PV modules-GB” is the point of intersection M of these characteristics: two modules connected in series and a storage battery. Diodes VD1 and VD2, called bypass diodes or bypass connects in parallel with each module or group of modules connected in parallel (see Fig. 3.77a). Bypass diode limits the reverse voltage, if a circuit module in a row is less efficient or is shaded and avoids thermal overstress. In normal operating mode diodes VD1 and VD2 do not consume energy.

Diode VD, called anti-return, is connected in series with the load. This diode prevents the situation when the PV module can become energy consumer, if the generated voltage will be less than the battery voltage. It is obvious that it introduces a voltage drop of about 0.5 V and, accordingly, loss of energy. Figure 3.77b shows a parallel connection of two identical modules. The voltage output remains the same and the current increases twice.

Fig. 3.76 PV module manufactured by Kyocera, Japan [61]



Table 3.15 Technical data of PV modules, manufactured by Kyocera Company [61]

Technical data	Type of module							
	KC35	KC40	KC45	KC50	KC60	KC70	KC80	KC120
Maximum output (W_C)	35.0	40.0	45.0	50.0	60.0	70.0	80.0	120.0
Maximum voltage (V)	15.0	16.9	15.0	16.7	16.9	16.9	16.9	16.9
Maximum current (A)	2.33	2.34	3.00	3.00	3.55	4.14	4.73	7.10
Idle running voltage (V)	18.8	21.5	19.2	21.5	21.5	21.5	21.5	21.5
Short-circuit current (A)	2.50	2.48	3.10	3.10	3.73	4.35	4.97	7.45
Length (mm)	471	526	573	639	751	865	976	1,425
Width (mm)	652	652	652	652	652	652	652	652
Thickness (mm)	52	52	54	54	52	56	52	52
Mass (kg)	4.0	4.5	4.5	5.0	6.0	7.0	8.0	11.9

Operating point of the system “PV modules – resistance R ” is the point of intersection M of the volt-ampere characteristics of the module and consumer – $I = (1/R) \cdot U$. Anti-return diodes VD11 and VD12 do not allow a module or a group of modules connected in parallel to pass under the consumer regime, when they are not identical or when they are shaded.

In Fig. 3.77c modules PV1-PV2, PV3-PV4 and PV5-PV6 are joined in series, but between them – in parallel. Thus, we obtain a double increase of the voltage and a triple increase of the current. Obviously, the unit power increases six times.

VD1-VD6 are bypass diodes and VD12, VD34, VD56 – are anti-return diodes. The parameters of a PV module are determined by the cell parameters.

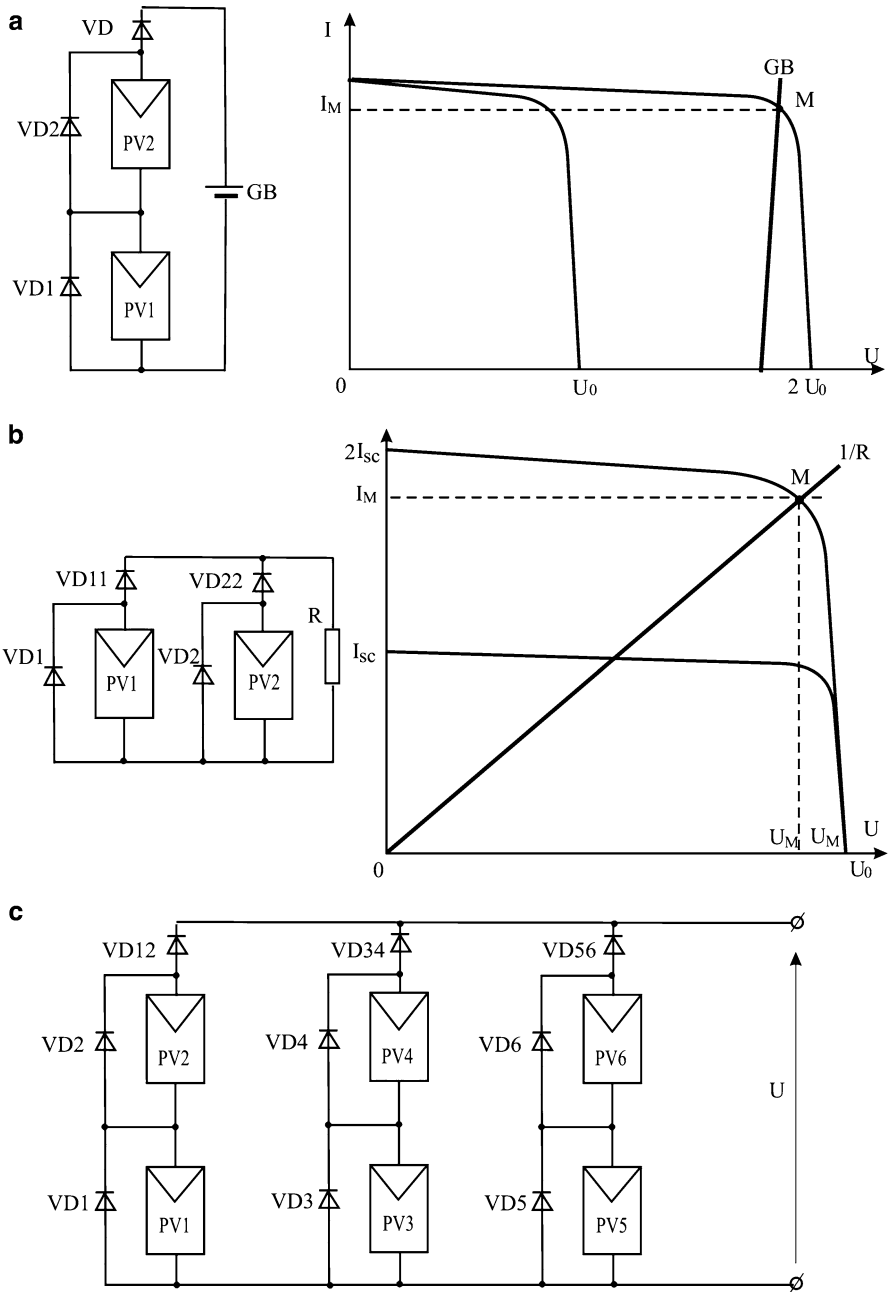


Fig. 3.77 PV modules interconnection: (a) in series; (b) in parallel; (c) in series-parallel

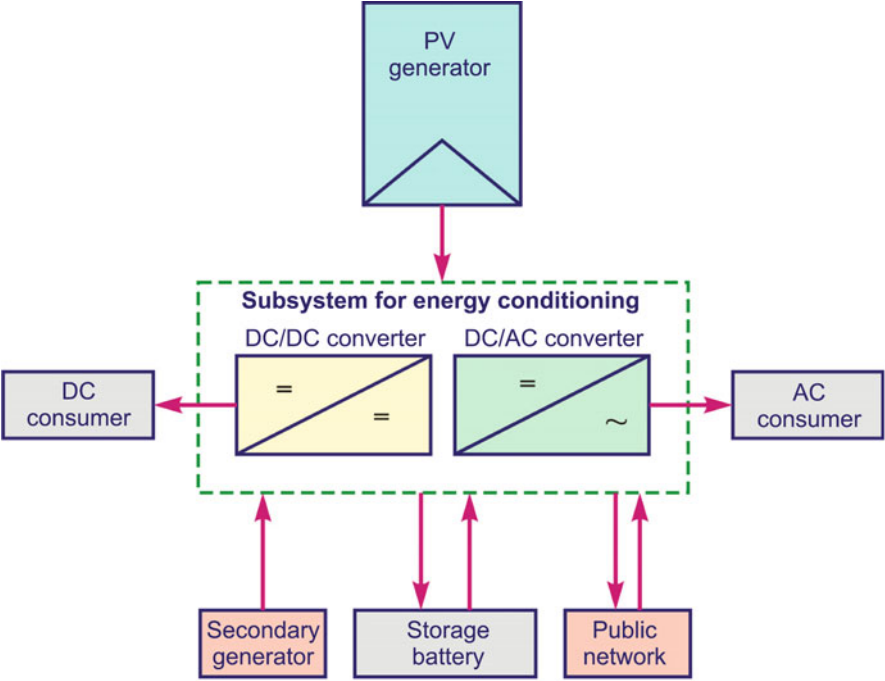


Fig. 3.78 Photovoltaic system structure

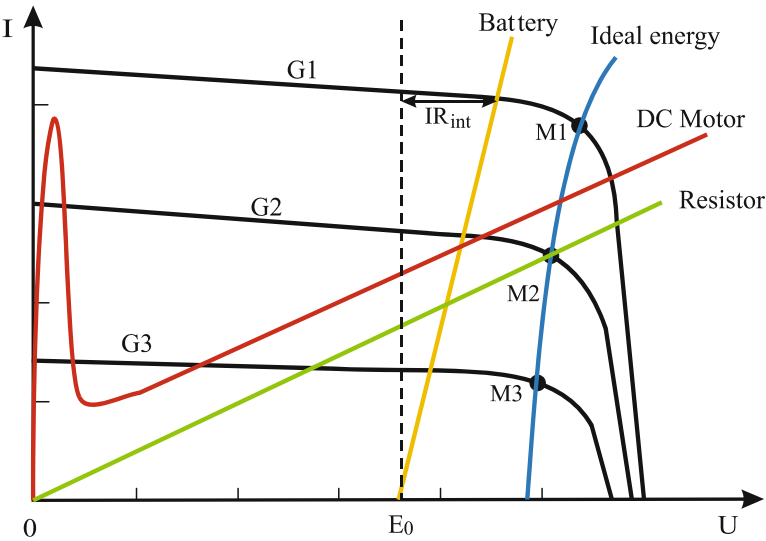


Fig. 3.79 I - V characteristics of three of the most widespread consumers

Further analysis will determine a numerical example for PV module parameters, operating in specified weather conditions

Numerical example: Determine the parameters of PV module consisting of 36 cells. The module operates under the following conditions: global radiation $G = 800 \text{ W/m}^2$, environment temperature $T_a = 30^\circ\text{C}$. Manufacturer of PV module guarantees the following parameters in the standard operating conditions:

- Short-circuit current, $I_{scst} = 3 \text{ A}$;
- No-load run voltage, $U_{0st} = 20.5 \text{ V}$;
- Critical (maximal) power, $P_{Cst} = 50 \text{ W}$;
- Cell normal operating temperature, $NOCT = 45^\circ\text{C}$.

Solution:

1. *Short-circuit current:* According to Eq. 3.72

$$I_{sc}(G) = (G/G_{st}) \cdot I_{scst} = (800/1000) \cdot 3 = 2.4 \text{ A}.$$

2. *Cell temperature.* According to Eq. 3.71:

$$T_C = T_A + \left(\frac{NOCT - 20}{0,8} \right) \cdot G = 30 + 25 = 55^\circ\text{C}.$$

3. *No-load run voltage.* The following expression is applied Eq. 3.73:

$$\begin{aligned} U_0(55^\circ\text{C}) &= U_{0st} - 0,0023 \cdot n_c \cdot (T_C - 25) \\ &= 20.5 - 0,0023 \cdot 36 \cdot 30 = 18.0 \text{ V}. \end{aligned}$$

4. *Fill factor.* According to Eq. 3.68:

$$FF = \frac{P_C}{U_{0st} I_{scst}} = \frac{50}{3 \cdot 20.5} = 0.81.$$

5. *Maximal power.* Determined if the FF factor does not depend on solar radiation and PV cell temperature:

$$P_C = FF \cdot U_0(55^\circ\text{C}) \cdot I_{sc}(G) = 0,81 \cdot 18 \cdot 2,4 = 35 \text{ W}.$$

3.3.5.4 Photovoltaic Systems

The structure of a photovoltaic system: PV cells or modules are not the only components of a PV system. To provide continuously electricity to the consumer, PV systems include more power batteries. PV module has a DC generator (DC), but often the consumer is AC power. PV electricity has a variable character. The alternating day/night process and clear/overcast sky causes a wide variation in the energy

flux and stress generated by the PV module. Thus, there is need for conditioning the power flux using electronic converters: DC/DC, which also has monitoring function of the charge/discharge process of the battery, DC/AC – to transform DC into AC. To avoid over sizing of the photovoltaic system, an auxiliary power source often is used: a generator or a wind generator or even public electricity network.

All these components must be interconnected, designed and specified to operate in a single system, the so-called photovoltaic system. Figure 3.78 shows the structure of a PV system. Its main components are:

- Module, panel, module field or otherwise said photovoltaic generator. PV generator characteristics and parameters have been analysed in Sect. 3.3.5.2;
- Battery charging system;
- Subsystem for electrical energy conditioning including measuring, monitoring, protection, etc. elements;
- Auxiliary energy source, for example, an electrogen group (*back-up generator*), that works on gasoline or diesel. In this case, the PV system is called hybrid photovoltaic systems.

PV systems are divided into two main categories: connected to the grid (*grid-connected*) or operating in parallel with the public electricity grid and autonomous PV systems (*stand – alone PV system*). The simplest system is the PV system for pumping water, the DC pump motor being used. This system does not contain electric batteries (water tank serves as a battery) or AC/DC converters.

Grid-connected PV systems can be divided into: PV systems, in which the public electricity network serves as a secondary source of energy (*grid back – up*); PV systems, in which the excess PV energy is supplied to the network (*grid interactive PV system*) and PV power stations (*multi-MW PV system*), which provides all the energy produced in the network.

PV module load operation: In Sect. 3.3.5.2 it was noted that PV cell, the PV module respectively, has the best performance at point *M* (see Fig. 3.73), and where the load delivered power is maximum. However, variation of overall radiation and temperature changes cause changes of PV module *I-V* characteristics.

Also, different consumers have different *I-V* characteristics. As a result, the operating point of PV module subsystem – load (the intersection of *I-V* characteristics of the module and load) will not coincide with the point *M*. In Fig. 3.79, *I-V* characteristics of three of the most widespread consumers are presented: resistor, DC motor with permanent magnet and a battery. The properties of an ideal consumer are presented for which the point of operation coincides with the optimal point *M*. *I-V* characteristics are described with the following analytical expressions:

- Resistor
$$I = \frac{1}{R}U; \quad (3.74)$$

- DC motor
$$I = \frac{U - E}{R_i} = \frac{U - k\Omega\Phi}{R_i}; \quad (3.75)$$

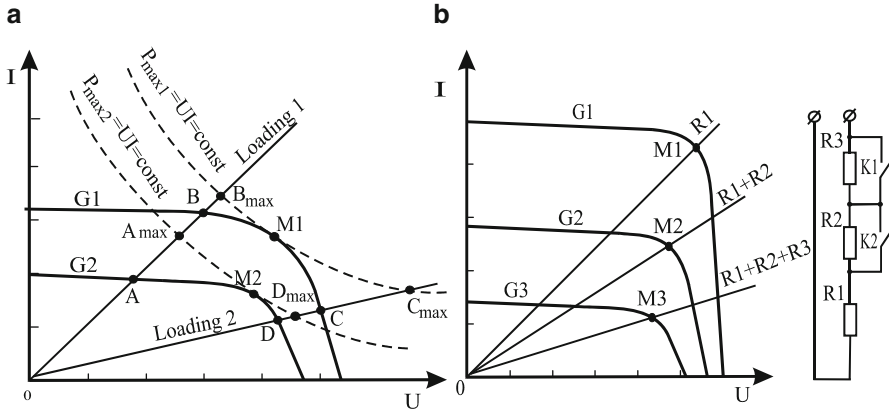


Fig. 3.80 Maximum output diagram: (a) employing MPPT technology; (b) by modifying load characteristics

- Battery
$$I = \frac{U - E_0}{R_{int}}, \quad (3.76)$$
- where U is PV module stress; k – motor constant; Φ – flow of excitation; Ω – rotational speed; R_i – armature resistance; E_0 – battery no-load voltage; R_{int} – internal resistance of battery.

When starting the DC engine, the input current drawn from the module is up and is close to the short circuit. Although the induced voltage is minimal its starting occurs due to the product created $k\Phi I_{sc}$. If $U = E_0$, the battery is charged and will not consume power, otherwise charging current will increase with increasing global radiation, and with the voltage respectively. Voltage drop IR_{int} increases with increasing load current.

Figure 3.79 shows that resistor type load or DC motor will not operate optimally in the optimum point of changing radiation. You will need to amend I - V characteristics of PV module or of the load to track the optimal operating point. To this end, they use DC/DC electronic converters called MPPT (Maximum Power Point Tracker).

MPPT connects between the PV module and the load to change the output voltage so as to ensure optimum operating point tracking. Figure 3.80 demonstrates two cases of the maximum point tracking – using MPPT technology (Fig. 3.80a) and by changing the load (Fig. 3.80b). In the first case, we have two loads with different I - V characteristics, which, for simplicity, linear allowed. For both tasks we find an essential deviation of operating points A , B and D , C from the optimal points $M1$ and $M2$. Hyperbolas $I = P_{max,1}/U$ and $I = P_{max,2}/U$ are drawn in the same coordinates. At any point of mentioned hyperbolas, power $P_{max,1}$ or $P_{max,2}$ are constant sizes and respectively equal to the maximum rated power in point $M1$ or $M2$.

Table 3.16 Performance parameters of main types of invertors (rectifiers) [59]

Parameters	Rectangular voltage	Quasi-sinusoidal or unit step	Time impulse modulation
Rated output (kW)	Up to 1,000	Up to 2.5	Up to 20.0
Overload factor	Up to 20	Up to 4	Up to 2.5
Efficiency (%)	70–98	>90	>90
Harmonic (wave form) distortion (%)	Up to 40	>5	<5

It is considered that the subsystem PV module – work load 1 operates in point *B* in conditions of global radiation equal to G_1 . To get the maximum power from the module load *I-V* characteristics should be modified, so as to cross in point *M1*. The same result can be achieved if the voltage decreases and current increases in comparison with *M1* point, moving on the hyperbola in B_{max} point, similarly if radiation reduces from G_1 to G_2 . For task 2, to track the maximum point it is necessary to do the opposite – to increase the voltage and to decrease the current (C_{max} will be compared to C or D_{max} with D). Electronic converter MPPT should vary the voltage and current so that their product at outlet to be constant and equal to the maximum power generated by PV module exposed to global radiation G . In some specific cases, the maximum power point tracking can be achieved by changing the load *I-V* characteristics, as shown in Fig. 3.80b. For maximum solar radiation, equal to G_1 , the subsystem PV module-load *R1* will operate at the point *M1*; in which case contacts *K1* and *K2* are closed. *K2* contact opens at the average value of solar radiation equal to G_2 , the load *I-V* characteristics changes and the subsystem will operate at point *M2*. If solar radiation continues to decrease, contact *K1* opens and the subsystem will operate at point *M3*. Subsystem “PV module – battery” does not require the use of MPPT technology, because if *I-V characteristic* moves to the right (Fig. 3.79) it will be close to that ideal. On the contrary, the battery requires automatic monitoring of the degree of loading and unloading to avoid its damage.

Designer’s decision to use or not use MPPT technology will be taken as a result of economic estimation. The following should be taken into account: MPPT converter cost, energy losses in MPPT (modern DC/DC converters efficiency is 90–95%) and power gain under optimal MPPT operation subsystem. According to available data [60], the maximum power point tracking in pumping PV systems increases the rated output by at least 20%.

Inverter: Inverter is part of the power conditioning subsystem of PV system (see Fig. 3.78) and is the main component of the converter DC/AC. Inverter converts DC energy generated by PV modules or stored in the batteries into AC energy of predetermined frequency. Converters have been already designed which provide power quality parameters at the same level as public networks: steady frequency and voltage, sinusoidal form of the voltage wave and current. Depending on load requirements on the voltage waveform, the overload factor, efficiency, different types of inverters are available, which parameters are presented in Table 3.16.

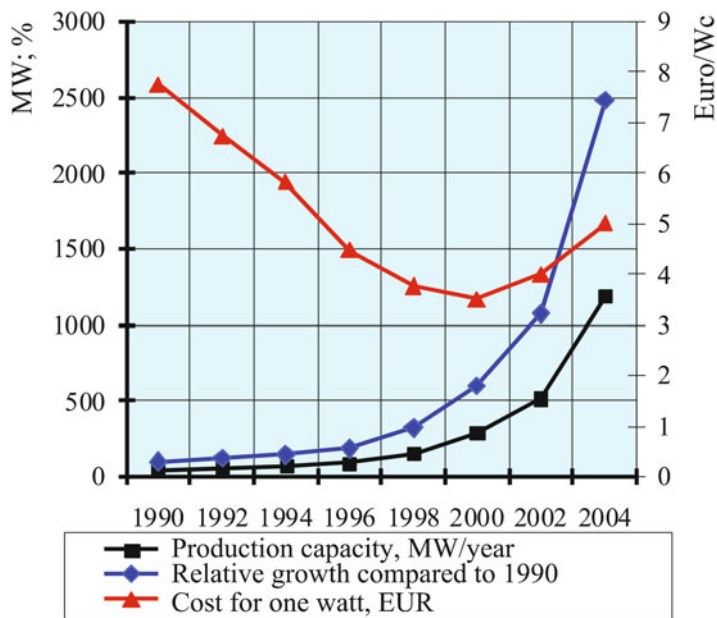


Fig. 3.81 Evolution of PV module world production

Indicated efficiency corresponds to inverter's operation at a load of 75–100% of rated output. When choosing the inverter it is important to know the characteristic of efficiency as a function of load. Motors require a starting current much higher than the nominal one. It is important that the inverter's overload factor meets this requirement.

Rectangular wave inverter has the simplest scheme, a relatively good efficiency, is the cheapest, but it causes the highest harmonic distortion, which causes engine overheating. This type of inverter is recommended for use in low power PV systems for lighting, heating at other than DC voltages, also in the composition of DC/DC converters, electromagnetic actuators. Quasi-sinusoidal wave inverter is more complicated, but relatively efficient. The pulse duration modulation technology is newer. Inverter control scheme is much more complicated, the cost of the inverter is higher, but also ensures high efficiency and minimum harmonic distortion.

3.3.5.5 Development Potential of Photovoltaic Systems

Figure 3.81 shows the evolution of global production of PV cells and modules and the cost of a watt in the period 1990–2004. After 1996 there is an extraordinary increase in worldwide production. In the years 2002–2004, growth compared with the previous year was equal to 28.2; 79 and, respectively, 60.5%. Over a period of 15 years, global production capacity of PV modules has increased about 25 times.

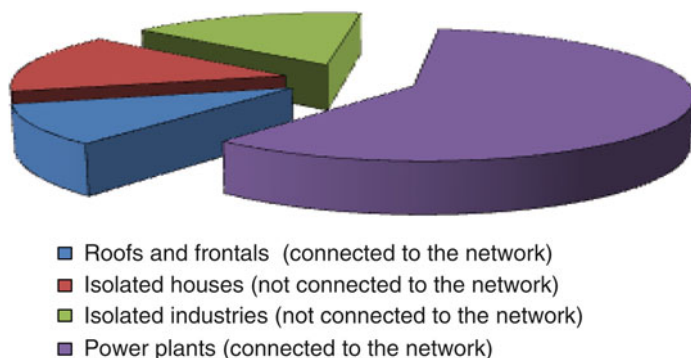
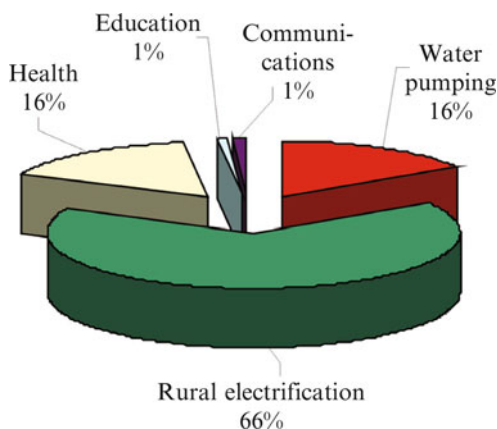


Fig. 3.82 Use of PV systems in developed countries

Fig. 3.83 Use of PV systems in under-developed countries



This trend will increase in the coming years as more oil companies (Shell, British Petroleum) will be involved in the new national programs. Along with the growth of production, photovoltaic cells become lower in cost. Over a period of 10 years the cost of a watt has decreased by 2.35 times. After 2000 there is an increase in the cost of a watt, which is explained by the formation of a gap between global production capacity of cells and assembly of PV modules and the production of raw material – pure silicon. Currently, worldwide there has been a shortage of raw material.

Areas of use in developed and developing countries are different (Figs. 3.82, 3.83). For example, in EU the PV systems are connected to the grid by 68%, in and developing countries there are three main areas of PV electrical energy use: rural electrification, health and water pumping. All these systems operate in autonomous mode, in other words, are decentralized and dispersed territorially.

Installed power worldwide was about 1,194 MWe in 2004, the first three places were occupied by Japan with 51.8%, followed by the EU with 25.8% and the U.S. with 11.5% (Fig. 3.84).

Fig. 3.84 PV installed capacity distribution in 2004 at world level

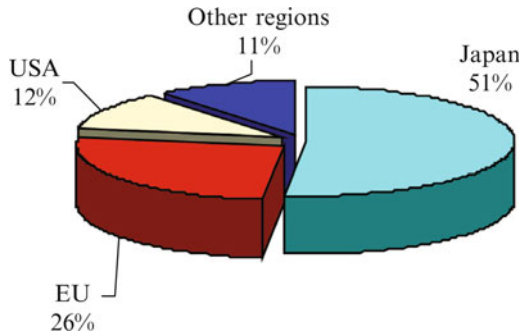


Table 3.17 Main national programs for promotion of PV energy and allocated subsidies

Country	National program	Acquisition price (Euro/kWh)	Subsidies (Euro/W _c)
Japan	70,000 solar roofs	0.3	1.13
USA	1,000,000 solar roofs	N/A	Differs by state
Germany	100,000 solar roofs	0.5	0.75–1.0
Great Britain	70,000 solar roofs	N/A	N/A 32 mln. Euro envisaged
Austria	–	0.72	Differs by region
Spain	–	0.47	5.5 autonomous systems 2.6 grid connected
Italy	10,000 solar roofs	0.35–0.40	70% of cost
France	–	0.15–0.3	4.6
Switzerland	–	0.3–0.6	1.3–2.7

N/A information not available

PV electrical energy is more expensive and in most cases do not compete with energy from fossil sources. Exceptions are pumping PV systems and systems for small and territorially dispersed power consumers, a case that can be compared with electrogen groups or with the extension of public power grids. Therefore, in various countries of the world, in national programs promoting PV energy, various methods have been developed to support and subsidize PV electrical energy (see Table 3.17).

The cheapest PV electrical energy can be obtained from the systems connected to public electricity networks, in other words, operating in parallel with the network. The system has the simplest configuration (modules field plus frequency converter), and there is no need for electric batteries. In 2005, photovoltaic electricity generation costs reached 50 cents/kWh in the Central Europe, reducing by 25 Eurocents/kWh in areas with high solar radiation. This cost can be compared to the cost of electricity produced from fossil sources, which in 2005 varied in the world between 0.04 and 0.05 \$/kWh. Note that the cost also depends on the duration of solar cells life. C-Si solar cells have 25 years warranty, but can be used 35 or even more years. Electricity costs spent on PV cells production can be recovered in the first 2 years (Fig. 3.85) [63].

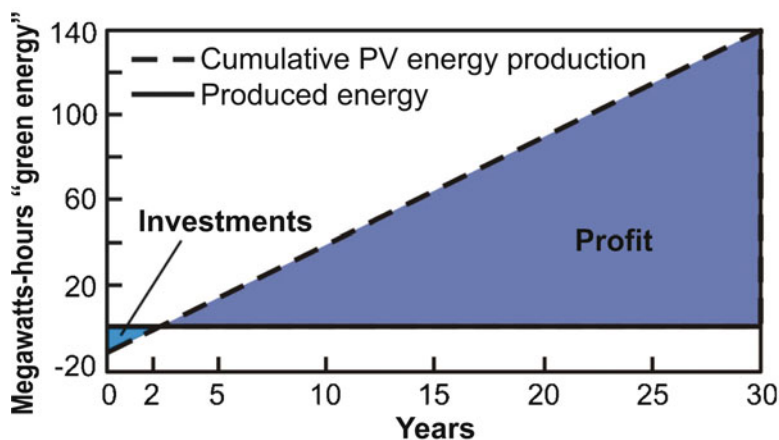


Fig. 3.85 Cumulation of PV energy production

Photovoltaic systems are evolving in terms of reducing manufacturing costs. Research is carried out on different semiconductor materials, and on PV cells manufacturing technologies. From this point, the evolution of the most efficient solar cells over the past 30 years (period 1975–2005) for different materials and technologies is of interest, according to NREL (National Renewable Energy Laboratory, USA) research. Areas where ice-photovoltaic cells find use on a more wide-scale are isolated consumers of electrical energy. Solar energy technologies use sunlight to produce heat, lighting, hot water and even air conditioning for residential and industrial areas. Solar panels are one of the most popular alternative energy sources used for private and industrial power systems.

According to the report of the International Energy Association (IEA) in 2004, it was an important year in terms of increase in the installed capacity of photovoltaic systems – from 770 MW, at the beginning of the year, to 2.6 GW by the end of 2004. The absolute majority of those capacities (94%) were installed in Germany, Japan and the U.S. (Table 3.18). Figure 3.86 presents the increase in photovoltaic electricity installed capacity since 1992 and the separation of this capacity between the two primary forms of using them.

Cumulative market in the countries with PV energy systems has achieved a growth rate of 42% between 2003 and 2004 and over 37% last year. A very large market for photovoltaic systems has been recorded in Germany (137%). Analysis of historical perspectives of the installation of photovoltaic systems in the countries with PV systems (Table 3.19) shows a spectacular development of PV systems in Germany (an increase of more than 140 times in 2004 compared to 1992) and Japan (over 60 times.). This tremendous growth continues to be developed for market support mechanisms, which initially was aimed at domestic applications in urban or suburban environments.

Table 3.18 PV installed capacity in AIE countries at the end of 2004

Country	Cumulative PV power (kW)		Total PV installed capacity (kW)	Total installed capacity per capita (W/capita)	PV installed capacity in 2004 (kW)
	Domestic	Non-domestic			
Australia	15,900	29,640	52,300	2.60	6,670
Austria	2,687		19,180	2.37	2,347
Canada	5,291	8,081	13,884	0.44	2,054
Switzerland	2,810	290	23,100	3.12	2,100
Germany	26,000		794,000	9.62	363,000
Denmark	65	190	2290	0.43	400
Spain	14,000		37,000	0.87	10,000
France	12,500	5,800	26,300	0.44	5,228
Great Britain	193	585	8,164	0.14	2,261
Israel	653	210	886	0.13	353
Italy	5,300	6,700	30,700	0.55	4,700
Japan	1,136	83,109	1,131,991	8.87	272,368
Korea	461	4,898	9,892	0.21	3,454
Mexico	14,169	4,003	18,182	0.17	1,041
The Netherlands	4,769		49,079	3.01	3,162
Norway	6,438	375	6,888	1.50	273
Portugal	1,657	569	2,643	0.25	574
Sweden	3,070	602	3,866	0.43	285
USA	77,900	111,700	365,200	1.24	90,000
Total estimated	170,730	281,021	2,595,545		770,270

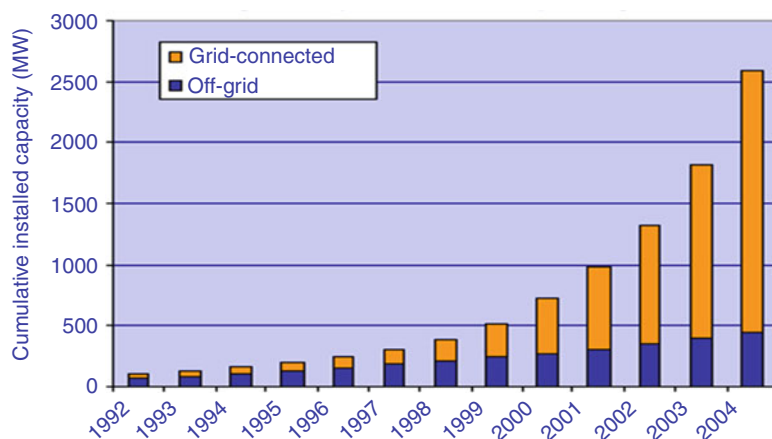
**Fig. 3.86** PV power installed capacity, grid connected and separated in the countries from Table 3.18

Table 3.19 PV cumulative installed capacity in AIE countries

Country	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Argentina	7.3	8.9	10.7	12.7	15.7	18.7	22.5	25.3	29.2	33.6	39.1	45.6	52.3
Australia	0.6	0.8	1.1	1.4	1.7	2.2	2.9	3.7	4.9	6.1	10.3	16.8	19.2
Austria	1.0	1.2	1.5	1.9	2.6	3.4	4.5	5.8	7.2	8.8	10.0	11.8	13.9
Canada	4.7	5.8	6.7	7.5	8.4	9.7	11.5	13.4	15.3	17.6	19.5	21.0	23.1
Switzerland	0	0.1	0.1	0.1	0.2	0.4	0.5	1.1	1.5	1.5	1.6	1.9	2.3
Germany	5.6	8.9	12.4	17.7	27.8	41.8	53.8	69.4	113.7	194.6	278.0	431.0	794.0
Denmark	4.0	4.6	5.7	6.5	6.9	7.1	8.0	9.1	12.1	15.7	20.5	27.0	37.0
Spain	0.9	1.0	1.2	1.3	1.5	2.0	2.2	2.3	2.6	2.7	3.1	3.4	
France	1.8	2.1	2.4	2.9	4.4	6.1	7.6	9.1	11.3	13.9	17.2	21.1	26.3
Great Britain	0.2	0.3	0.3	0.4	0.4	0.6	0.7	1.1	1.9	2.7	4.1	5.9	8.2
Israel	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.8
Italy	8.5	12.1	14.1	15.8	16.0	16.7	17.7	18.5	19.0	20.0	22.0	26.0	30.7
Japan	19.0	24.3	31.2	43.4	59.6	91.3	133.4	208.6	330.2	452.8	636.8	859.6	1,132
Korea	1.5	1.6	1.7	1.8	2.1	2.5	3.0	3.5	4.0	4.8	5.4	6.4	9.9
Mexico	5.4	7.1	8.8	9.2	10.0	11.0	12.0	12.9	13.9	15.0	16.2	17.1	18.2
The Netherlands	1.3	1.6	2.0	2.4	3.3	4.0	6.5	9.2	12.8	20.5	26.3	45.9	49.1
Norway	3.8	4.1	4.4	4.7	4.9	5.2	5.4	5.7	6.0	6.2	6.4	6.6	6.9
Portugal	0.2	0.2	0.3	0.3	0.4	0.5	0.6	0.9	1.1	1.2	1.7	2.1	2.6
Sweden	0.8	1.0	1.3	1.6	1.8	2.1	2.4	2.6	2.8	3.0	3.3	3.6	3.9
USA	43.5	50.3	57.8	66.8	76.5	88.2	100.1	117.3	138.8	167.8	212.2	275.2	365.2
Total	110	136	164	199	245	314	396	520	729	989	1,334	1,829	2,596

3.3.5.6 Photovoltaic System Dimensioning

The general principle underlying the PV system dimensioning is to always respect the balance between the energy produced by PV generator and the consumed energy. This balance is achieved for a defined period, usually a day or a month. Presence of the storage (secondary or storage cells) battery allows compensation of the shortfall between the produced and consumed energy, which may be due to cloudy weather or overloading on behalf of the consumer.

Sizing a PV system requires the following basic steps:

1. Calculation of available solar radiation on the surface of PV module;
2. Daily electricity consumption calculation – E_c ;
3. Calculating the amount of electrical energy needed to be produced by PV module – E_p ;
4. Calculation of critical power of PV module – P_c and its choice;
5. Calculation of battery capacity – C and choice of batteries;
6. Checking electrical energy consumption and generation balance.

Figure 3.87 shows the procedure for sizing a PV system with storage battery.

Calculation of available solar radiation on the surface of PV module is made in accordance with the method described in Sects. 3.2.3.2 and 3.3.2.7. PV module inclination angle to the horizon β is determined from the condition ensuring the equilibrium “consumption – electrical energy production” in the months with the lowest solar radiation.

Daily electricity consumption calculation: To this end, for every consumer of DC and AC nominal power and hours of daily consumption are determined. Electrical energy consumption E_C is determined as the output of nominal power to the number of hours:

$$E_C = \sum_{i=1}^k \frac{P_{ni}^{cc} \cdot t_i}{\eta_R \cdot \eta_{Ac}} + \sum_{j=1}^m \frac{P_{nj}^{ca} \cdot t_j}{\eta_{CF}} \quad (3.77)$$

where k is the number of DC consumers; m is the number of AC consumers; P_{ni} , P_{nj} is the nominal power of Dc and AC consumers; t_i , t_j – operating period of the given consumers; η_R , η_{CF} , η_{Ac} – efficiency of battery charge – discharge controller and the frequency converter. For preliminary calculations $\eta_R = 0.95$ – 0.98 , $\eta_{Ac} = 0.85$ – 0.90 , $\eta_{CF} = 0.85$ – 0.95 . Electrical equipment nominal powers are specified in the technical book. However, they can be made available to the designer by the company producing these machines. The values of operating times per day of the equipment are obtained from the beneficiary’s stated needs or are determined from statistical data.

Some technical data of household consumers: [59, 64, 65]. Further on, some technical data on the most usual estimates of household electricity consumers follows: rated output, efficiency, lifetime, etc. (Tables 3.20, 3.21).

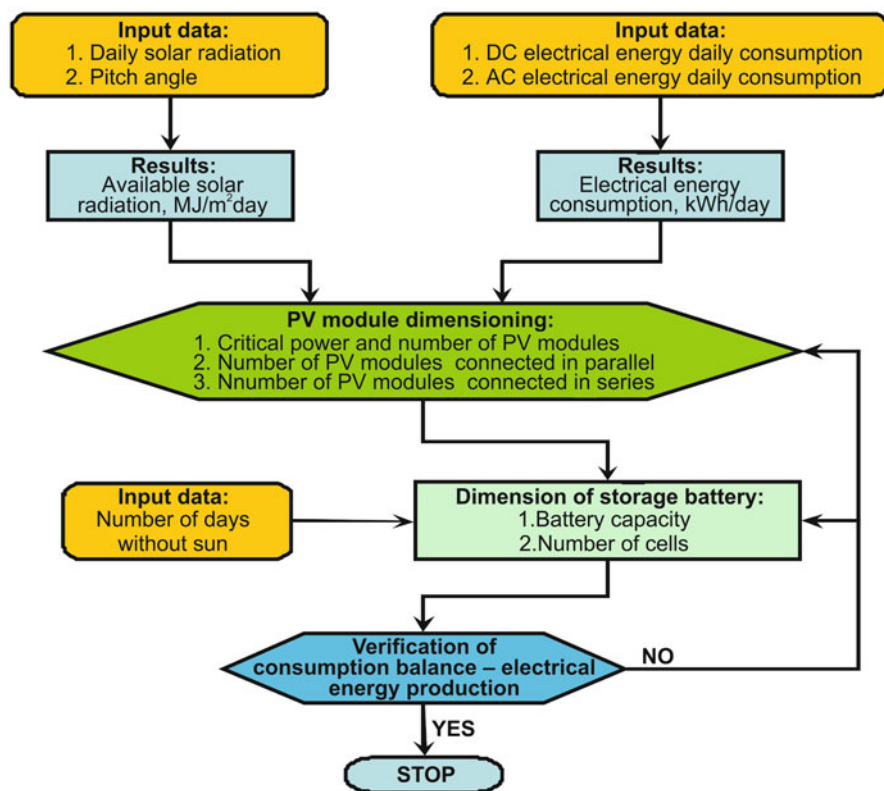


Fig. 3.87 Photovoltaic system dimensioning

Table 3.20 Lighting source

Lighting source	Power (W)	Efficiency (lm/W)	Lifetime (h)
Electric bulb	25	9.0	2,500
Electric bulb	40	9.0	1,000
Electric bulb	75	13.0	1,000
Electric bulb	100	16.0	1,000
Electric bulb (crystal, quartz)	50	19.0	2,000
Compact fluorescent lamp (CFL)	4	45.0	6,000–10,000
	8		
	13		
	18		
Fluorescent (luminous) lamp T-8	n/d	75–100	12,000–24,000
Halide lamp	n/d	80–115	10,000–20,000
Low pressure sodium lamp	35	128.0	5,000
LED surface	3.6	130.0	>100,000
High pressure sodium lamp	n/d	90–140	10,000–24,000

Table 3.21 Estimative values of functioning period of electrical energy consumers for an isolated house

Consumer	Rated output (capacity) (W)	h/day		
		Months		
		XII,I,II	III,IV,V,IX,X,XI	VI,VII,VIII
Lighting kitchen	2 × 13 LFC	4.0	3.5	2.0
Lighting bedroom	3 × 9 LFC	1.0	1.0	1.0
Lighting living room	2 × 20 LFC	1.0	1.0	1.0
Lighting bathroom	1 × 18 LFC	1.0	1.0	1.0
Vacuum cleaner	1,200	0.5	0.5	0.5
refrigerator	100	7.0	7.0	7.5
Colour TV, 54 cm	60	4.0	4.0	4.0
Stereo	60	2.0	2.0	2.0
Microwave oven	600	0.5	0.5	0.5
Water pump	200	1.0	1.0	1.0

Calculating the amount of electrical energy needed to be produced by PV module:
Electrical energy to be produced by PV module:

$$E_P = \frac{E_C}{K} \quad (3.78)$$

Where K factor takes into account the uncertainty of weather data, the losses in cables, the deviation of functioning point of the subsystem “*PV module – load*” from the optimum one, etc. According to [64], the value of K factor for PV systems with storage batteries is between 0.75 and 0.85.

Critical power of PV module is determined from the relation:

$$P_C = \frac{E_P}{G_\beta} = \frac{E_C}{K \cdot G_\beta} \quad (3.79)$$

where G_β shows the average global solar radiation during the period of interest in this locality for the angle of inclination β of the PV module. In the formula (3.79) G_β is equal numerically to the number of hours per day of standard solar radiation, that is equal to 1,000 W/m² and is noted by HRS .

Depending on power P_C , the power of PV module and the number of modules connected in series are selected:

$$N_S = \frac{U_{cc}}{U_m} \quad (3.80)$$

where U_{cc} is the nominal stress of AC consumers; U_m – nominal stress of a PV module that equals 12 V.

The number of PV modules connected in parallel is defined in the following way: the average current of load per day is estimated:

$$I_{med} = \frac{E_P}{24U_{cc}} \quad (3.81)$$

At the same time, respecting the condition of energy balance it is possible to write:

$$24 \cdot I_{med} \cdot U_{cc} = HRS \cdot I_{PV} \cdot U_{cc} \text{ or } I_{PV} = \frac{24I_{med}}{HRS} \quad (3.82)$$

where I_{PV} is PV panel current.

The number of PV modules connected in parallel will be:

$$N_P = \frac{I_{PV}}{I_{sc}} \quad (3.83)$$

where I_{sc} is the short circuit current of a PV module that is considered almost equal to the current in point M (see Fig. 3.86).

Calculation of battery capacity: It is determined from the relation:

$$C = \frac{n \cdot E_C}{K_D \cdot U_{cc}} \quad (3.84)$$

where n is the number of days without sun; K_D – battery discharge rate (0.5–0.6 for Pb–acid and 1.0 for Ni–Cd).

The number of batteries connected in series:

$$N_{As} = \frac{U_{cc}}{U_A} \quad (3.85)$$

Where U_A is the battery nominal stress, usually equal to 12 V.

Checking the balance of electrical energy consumption and generation: Verification is done by comparing the amount of electricity, E_i , that will be produced by the PV panel in a day for each month of the period of interest to the amount of electricity needed calculated as 2.77. Calculations made from the relationship:

$$E_i = HRS_i \cdot P_C \quad (3.86)$$

where HRS_i is the number of hours per day of standard solar radiation equal to 1,000 W/m² for the given month.

3.3.5.7 Fields of Use of Photovoltaic Electrical Energy

Solar energy is the most accessible of renewable energies. Anyone can use this free energy. Photovoltaic systems are often used in combination with other energy sources: wind, hydro or energy produced from burning fossil fuels.

A very important area for the use of photovoltaic systems is cosmic flight devices. Solar photovoltaic systems are practically the only source of electrical energy for



Fig. 3.88 PV systems installed on the first artificial satellite *Sputnik 3*

these devices. Soviet satellite *Sputnik 3*, launched on 15 May 1957, was the first satellite, which used photovoltaic systems (Fig. 3.88).

The first U.S. satellite, which used solar panels, was the U.S. Army Forces satellite “*Explorer 1*”, launched on 1 January 1958. Dr. Hans Ziegler, who worked for 30 years (1947–1976) in the field, may be called the father of solar energy systems for spacecrafts [66]. Since the device should have small dimensions, this fact limited the power that could be produced [67]. The requirements to solar panels were very rigid. Solar panels must include a driving mechanism for orientation to the sun (at the stage of electrical energy production) and removal from the sun when electrical energy needs were lower than the production capacity. Gallium arsenide was used as solar cells. Efficiency of gallium and silicon arsenide multi-junction cells reaches almost 29% in ideal conditions [68]. Such solar cells were also used in solar panels installed on “*Stardust*” spacecraft (Fig. 3.89), launched on 7 February 1999 to investigate the comet Wild 2 and returned on 15 January 2006. *Stardust* was the first cosmic mission returned to Earth after collecting a sample of cosmic dust.

European Space Agency (ESA) has developed a perspective project with real chances of its fulfilment, which investigates the possibility of launching satellites – solar power plants that will generate electrical energy in the space, transported afterwards to the earth by laser or microwaves. These outstanding achievements have become a cosmic challenge for the governments in the industrialized countries (Japan, Germany, U.S. and others) to bring solar cells on Earth. Terrestrial photovoltaic

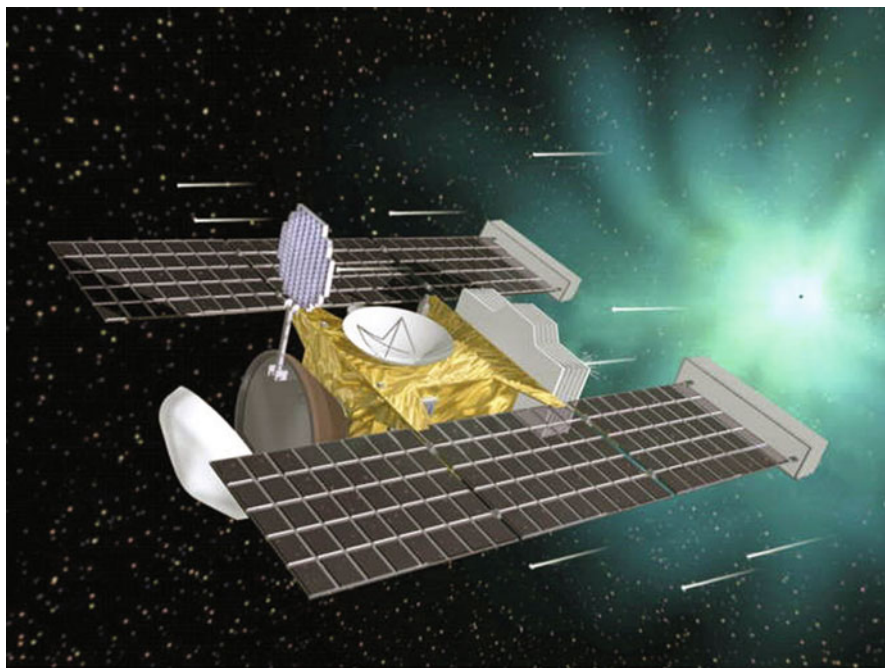


Fig. 3.89 Solar panels installed on the cosmic spacecraft Stardust (NASA image)

systems have been developed in two directions: using simple photovoltaic cells (without concentrating sunlight) and systems with focus sunlight on PV cells (CPV).

Today, there are two companies in the world that deal with developing concentrating photovoltaic systems (CPV): Amonix, in Torrance, California, USA and Solar Systems Pty Ltd, in Australia. Figure 3.90 shows a photovoltaic system, developed by Amonix Company, rotating around two axes (in zenithal and azimuthal planes), producing 25–35 kW on a mobile system (depending on the number of PV modules installed on the system). The Amonix system uses thousands acrylic Fresnel lenses that concentrate sunlight on solar PV cells. Annual Efficiency of Amonix module is 15.5%. Amonix systems were used in the public services with a total capacity of 547 kW in Arizona. 10–20 MW systems are scheduled for use in the near future in Spain. *Solar Systems Pty Ltd* uses paraboloidal concentrators to concentrate sunlight on the PV receiver. Figure 3.91 presents such a system, which achieves an efficiency of 15–16% and has a capacity of 220 kW, with the possibility of increasing the load up to 720 kW. More MW capacity contracts are coming in the near future. A new generation of approx. 50 MW of CPV systems will be produced in California, USA.

Solar panels with concentration of sunlight are widespread, especially in cases of isolated energy consumers. Figure 3.92 shows the use of a photovoltaic system on a yacht for charging 12 V and 9 A batteries. The solar panels have found wide use in



Fig. 3.90 Amonix system with concentrator with acrylic lenses and PV silicon cells (Source: NREL)



Fig. 3.91 PV paraboloidal concentrator: Solar Systems Pty LTD (Source: NREL)



Fig. 3.92 Photovoltaic system installed on a yacht to charge 12 V and 9 A cells

meeting domestic energy needs. Figure 3.93 shows a variant of photovoltaic systems connected to the electrical grid of a house, and Fig. 3.94 portrays an example of installing solar panels on the roof of a house.

At present decentralized rural electrification is accelerating fast by using solar energy, in particular, in the developing countries (LDCs). Although PV technology is considered expensive, the growth rate of world production of PV cells in 2000 constituted 60.5% (see Sect. 3.5.5). Why developing countries do not follow the same way passed by the European countries in electrification? The reasons limiting the application of traditional solution – thermal conversion of fossil fuel into electricity and its distribution via networks – are as follows:

1. Majority of rural consumers of electrical energy are located far away from the existing electrical networks and their density is low;
2. Electricity demand is low and falls within the range of 10–20 kWh/day;
3. Usually electrical energy is used for lighting, telecommunications and electric drive of small motorized equipment: electric pumps, small power workshop tools etc.

In these circumstances, traditional electrification is an inefficient solution in terms of both economic and environmental points: increase of investments and operating costs, increase of specific GHG emissions per capita calculated, as the efficiency of transport and distribution of 1 kWh of electrical energy decreases.

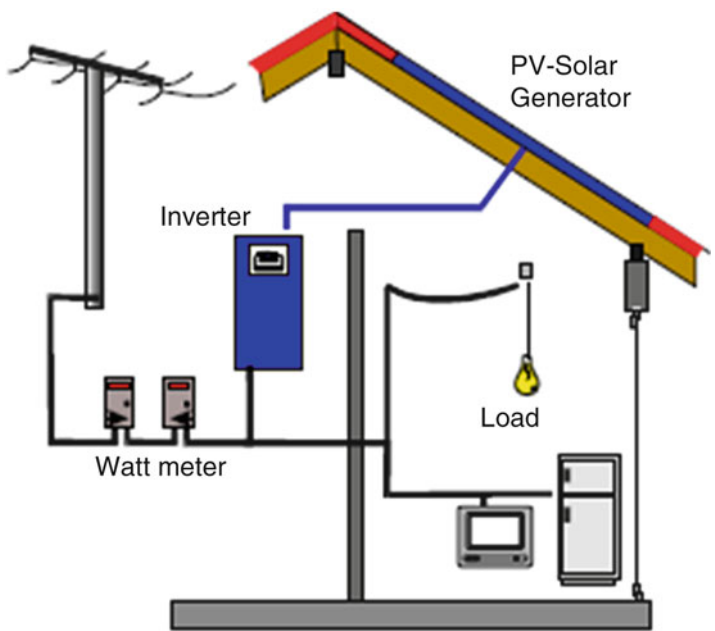


Fig. 3.93 PV grid connection in a living house



Fig. 3.94 Solar panels on the roof of a residential house

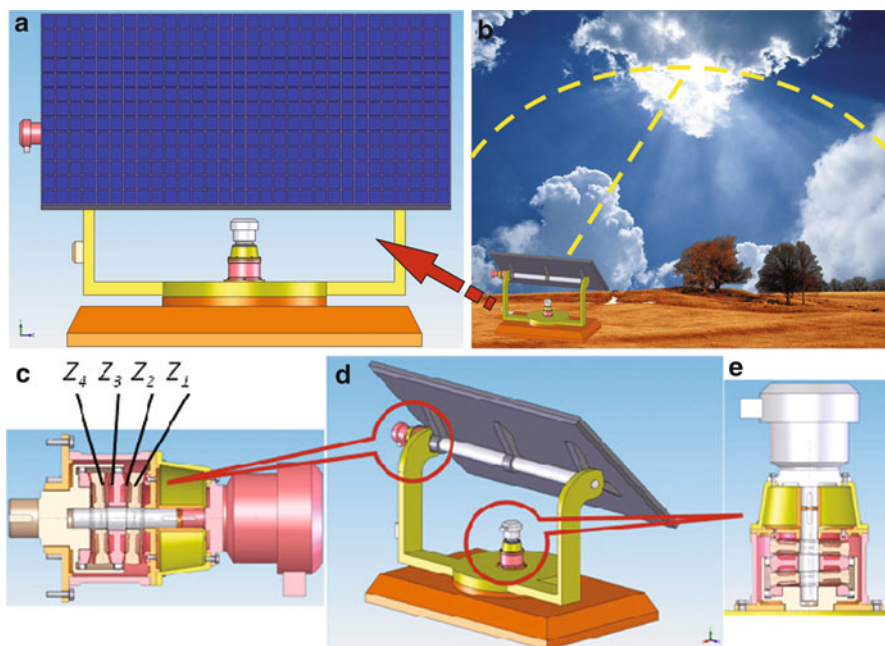


Fig. 3.95 Photovoltaic solar system orientation unit: author's elaboration

Photovoltaic panels orientation systems: It is known that the efficiency of a photovoltaic system depends largely on the orientation of the solar panels toward the sun standing both in azimuth and zenith. For this purpose they use different driving mechanisms. Because the motions of rotation around the two axes must be very slow (in the azimuthal plane the device must revolve from 10 to 16½ h), the gear ratio of these mechanisms (if done on the basis of gears) must be very high. Planetary gears (most common for such cases) should include 3–4 steps, which considerably increases the number of elements and hence their cost. In order to simplify construction and reduce costs of these orientation mechanisms, the research team of the Department of Theory of Mechanisms and Machine Parts, at the Technical University of Moldova, designed and patented the self-orientation solar unit conceptual diagram [69]. The photovoltaic panel is oriented to the sunlight, being rotated in azimuthal and zenithal planes by driving mechanisms with precessional transmission (Fig. 3.95). Very broad cinematic options of precessional transmissions ensure very slow rotation around the two axes (one revolution in 24 h). In the developed system, slow motions of rotation, necessary for the revolution of the solar panel in azimuthal and zenithal planes, are performed by precessional planetary transmissions in two steps: for the rotation of the solar system in the zenithal plane (Fig. 3.95c) and in the azimuthal one (Fig. 3.95e), subject to the motion of the sun in the sky (actually the earth rotating around the sun). Precessional transmission gear ratio in one step is determined from the relation:

$$i = \frac{Z_2 Z_4}{Z_1 Z_3 - Z_2 Z_4}, \quad (3.87)$$

where Z_1, Z_2, Z_3, Z_4 is the number of crown wheel serrated teeth (see Fig. 3.95c). A simple calculation shows that, to ensure rotation of the solar system in azimuthal plane within 24 h with a $1,500 \text{ min}^{-1}$ servomotor, reducer gear ratio must be equal to $i = 2,160,000$. To achieve this transmission ratio, it is recommended to choose the following gear ratios of the precessional gear reducer: for the first step less required $i = -2,115$ ($Z_1 = 46$; $Z_2 = 47$; $Z_3 = 46$; $Z_4 = 45$); for the second step $i = -1,023$ ($Z_1 = 32$; $Z_2 = 33$; $Z_3 = 32$; $Z_4 = 31$). To achieve this transmission ratio, a 5-speed planetary gear would be required, which includes at least 25 gear wheels; while the precessional gear reducer in two steps includes only four gear wheels and two satellite wheels with two toothed crowns. Relatively simple construction of the driving mechanism (to obtain a high transmission ratio, dictated by the necessity of very slow rotation, using a small number of elements), and high reliability ensures relatively low cost of the solar photovoltaic installation and long period of operation.

Based on the research, the authors have developed, designed and manufactured four types of photovoltaic systems for use in various fields. Figure 3.96a, c, shows a photovoltaic system endowed with four modules of solar cells with summary power of 700 W, installed in a common housing mounted on the support by the sun orientation mechanisms 4 and 5 (Fig. 3.96d). Figure 3.96b shows another option of assembling a photovoltaic system with two modules of solar cells. Orientation of photovoltaic panels to the Sun is done by two axes – the horizontal one with the angular extension of 95° through a solar motor Sun Tracer Pump 4 operated by the Time derived Astronomical Positioning System (TdAPS). Photovoltaic panels are oriented on the azimuth with angular extension of 75° through the drive mechanism 5 with 2 K-H type precessional gear with gear ratio $i = 144$, driven by a solar motor Sun Tracer + electric motor step by step. In this case the rotational motion of the drive shaft reduced by the gear ratio of planetary precessional transmission is forwarded to body on which the housing with solar panels is assembled (Fig. 3.96).

In order to simplify construction and reduce costs of these orientation mechanisms to the sun, the authors propose a tracking mechanism based on the use of shape memory material properties (Fig. 3.97 [62]). The orientation of paraboloidal solar unit includes a dead abutment 1, on which the rotating part 2 is installed with the paraboloidal concentrator 3. Receiver 4, the reflector 5 (mirror) and the electric generator (power unit) 6 are also linked to the rotating part 2. Disk 7 is fixed rigidly on the rotating part 2; on disk 7 whose area is equal to 180° curvilinear elements 8 are fixed, made of shape memory material (for example, nitinol alloy – NiTi), which were printed in the form of rectilinear memory. The free ends of the curvilinear elements 8 contact consecutively with asymmetrical teeth 9, designed on the front part of wheel 10, rigidly fixed to a support 1. Inside the rotating part 2 is located rod 11 with the bolt (pin, finger) 12, one end of which is located in the groove 13, designed on the area of 180° of the cylindrical inner surface of the rotating part 2, so that half of it is made with ascending angle and the second



Fig. 3.96 Photovoltaic system with solar astronomical orientation, assembled at the Centre for Renewable Energy Development, TUM

half – with the descending angle. The rod 11 is connected via levers 14 with the paraboloidal concentrator 3 housing Inside support 1 an electric motor 15 and a reducer 16 are placed, which shaft is connected to the rotating part 2 and the photocell 17. During the day solar unit occupies three extreme positions: in the morning, at sunrise, the parabolic concentrator is in the position when the angle of rotation (azimuthal) $\varphi_a = 0^\circ$ and the zenithal angle $Q_z = 0^\circ$; at noon, when the azimuthal angle $\varphi_a = 90^\circ$, and the zenithal angle is maximum Q_{zmax} ; at sunset, when the position of the azimuthal angle $\varphi_a \approx 180^\circ$ (do not take into account deviations of about $\pm 20^\circ$ related to the season: in summer $\varphi_a = 180^\circ + 20^\circ$, in

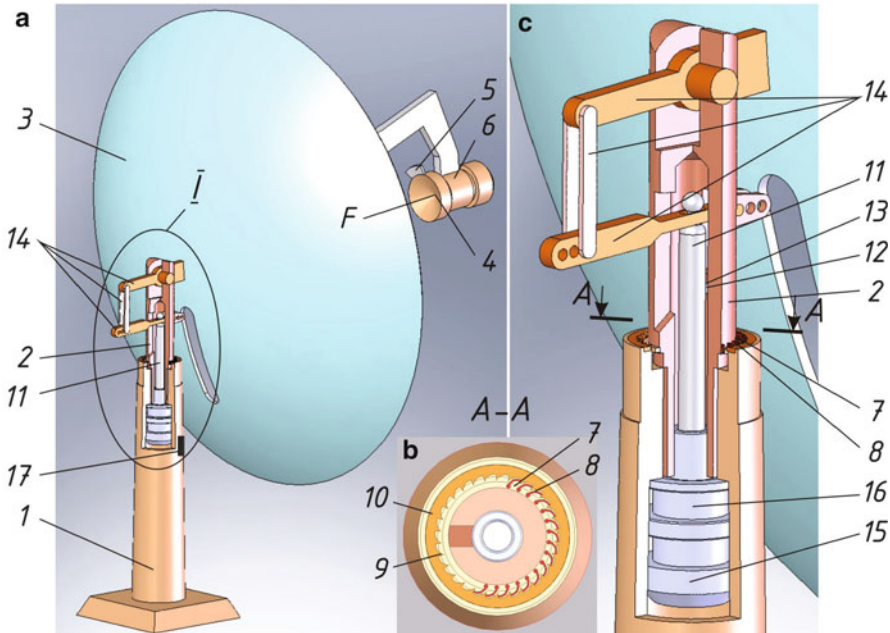


Fig. 3.97 Parabolic solar system orientation unit: author's elaboration

winter $\varphi a = 180^\circ - 20^\circ$) and the zenithal angle is equal to $Q_z = 0^\circ$, as well. To ensure the rotation of the paraboloidal concentrator in azimuth and zenith planes, the orientation system includes curvilinear elements with the shape memory 9. Number of curvilinear elements with shape memory 9 is chosen depending on the degree of discretion allowed for rotating motion in the azimuthal plane $\varphi_{ai} = 180^\circ / i$, where i is the number of curvilinear elements with shape memory 9. Angle φ_{ai} depends on the distance crossed by the focal point within the receiver's 4 length (when the rotating part is stationary). When the focal point goes outside the limits placed on the length of the receiver and mounts on reflector 5, the reflected concentrated rays are oriented towards curvilinear elements 8, warming them up to temperature of intercrystalline changes (for nitinol is equal 149°C) – a return to the memorized shape (rectilinear). The new rectilinear form, resumed by elements 8, leads to the rotation of the rotating part 2 and, also, of paraboloidal concentrator with angle φ_{ai} . To ensure placement of focal point F in the working space of reflector 5 and the zenithal plane, to the rotation of the rotating part 2, the bolt (finger) 12 moves in groove 13, ensuring lifting (or lowering) of the rod 11 that, through levers 14, rotate the paraboloidal concentrator in the zenithal plane. Bringing the solar paraboloidal unit in the original position (the position before sunrise) is performed by the electric motor 15 and reducer 16, at the signal of the photocell 17. At the same time, the shape memory elements 8 are deformed (to) the initial curvilinear shape. To take into account the factor of season (winter, spring – autumn, summer),

when the sun zenithal angles are different, system of levers is made adjustable. The orientation system of the designed paraboloidal solar plant provides orientation to the sun with a minimum of electricity (solar plant is self-controlling, without consuming electricity), increasing the efficiency of solar plant. Simple construction and low cost of the designed orientation mechanism ensures cost-value efficiency.

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